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MOTORCAR HEADLIGHTS

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In recent years an instrument has been constructed (the "icaroscope" of Brian O'Brien) by means of which it is possible to observe the sun and the surrounding sky simultaneously, owing to the difference in brightness, the factor of which is about 10 000, being reduced to a factor of 20 with the aid of an image obtained by an intermediate link (a phosphorescent substance) with a non-linear response.

Such would be an ideal solution of the well-known problem of glare from an oncoming vehicle when travelling by night, were it not for the fact that efficiency is very low, and this applies also for other attractive solutions, such as that with polarised light. Thus, for the present, so long as there is no alternative to the systems of headlights now being used, motorists have to put up with a certain amount of glare when passing each other. In respect to this glare and its consequences from the point of view of the distances of visibility obtainable, there has been for a number of years a controversy between two schools of thought in the field of motorcar lighting, namely the European (the oldest) and the American. The object of the present article is to give the reader an insight into the most important aspects of this subject and the trend of this controversy.

On headlights in general

When walking along a road in the dark it is handy to have a pocket torch with which to illuminate the ground a short way ahead, so as to avoid stumbling over unexpected obstacles. Modern lighting of motor vehicles comes to much the same thing, only the headlights have to answer much higher demands on account of the much greater speed of travel. The "short way ahead" that is to be illuminated has to be at least equal to the braking distance, i.e. the distance within which the vehicle can be brought to a standstill. In the case of a car travelling along at a speed of 80 - 100 km/hr, as is usual nowadays on highways, under normal circumstances this braking distance is about 80 metres. Actually, however, the driver should be able to see over a much greater distance than this, because if under normal conditions he is only just able to stop the car within that distance then accidents will soon happen in the case of minor failures (brakes not properly adjusted, slippery road, speed higher than the above-mentioned limit). Moreover, the braking distance is itself increased by the appreciable time it takes the motorist to react to the perception of an obstacle. This explains why in practice by day the motorist usually keeps his eye on the road 100 to 200 metres ahead.

To be quite sure of being able to see an obstacle ahead even when the contrast between the obstacle and the road surface is very unfavourable (e.g. a darkly-dressed pedestrian on a wet road), a vertical illumination of at least a few lux, say 5 lux, is needed on the obstacle. To get this illumination at a distance of say 100 metres from two headlights the luminous intensity of each light in the axial direction has to be about 25 000 cd.

With an incandescent lamp in a parabolic reflector this is easily reached. If B is the brightness of the filament and O the area of the reflector opening, then the luminous intensity in the axial direction is

$$I_{\mathrm{ax}} = aOB,$$

where a (< 1) is a factor allowing for the losses of light on the reflector and in the front glass. With

$B \approx 600$ cd/cm^2 (tungsten coil glowing at 2450 °C) and $O \approx 200$ cm^2 (reflector with diameter about 16 cm), before the luminous intensity drops below the said minimum the factor a may be as low as about 0.2, which would correspond to an extreme fouling or damaging of the optical system.

Of course a sufficient axial luminous intensity is not all that is required: the motorist must have a view of the road of a certain width and depth, so that the beam of light must have a certain horizontal as well as vertical spread. This leads, on the one hand, to a number of problems in regard to the construction of the bulb and the headlight, whilst on the other hand it is the source of one of the fundamental difficulties with motorcar headlights, namely the problem of the oncoming vehicle. When aiming at a sufficient spread of the beam, or, to be more exact, at the desired distribution of the light of the beam, it is almost inevitable that the luminous intensity of the headlight in the direction of the eyes of the driver of an oncoming vehicle becomes fairly great, so that both drivers suffer more or less from glare when they pass each other. Unless very drastic counter-measures are taken, such as complete separation of the traffic lanes on the road (cf. also the end of this article), this evil can only be remedied to a certain extent by sacrificing some of the desired distribution of the beam.

Now in practice, as may be presumed to be known, it is customary to use a separate beam of light when passing another vehicle. For normal travel, when there are no other sources of light on the road than those of one's own car, the "driving light" [1]) is used — a beam giving the best possible illumination of the road ahead under the limitations of power, etc. — and when approaching another vehicle travelling in the opposite direction the driver switches over to the "passing light" [1]), which is a compromise between the opposing requirements of optimum illumination and minimum glare. Of course one reckons on the other driver likewise switching over to his passing light.

Usually these two different beams of light are produced by two different filaments in one reflector. Two practical forms of this principle will be described below, where an opportunity will be afforded to deal briefly with the problems already mentioned arising in the construction of motorcar headlights. In this article, however, we shall discuss more particularly the distribution of the light in the two beams and the results that may thereby be obtained.

First we shall discuss the driving light and then the passing light.

The driving light

Statutory requirements; the 10-m screen

Let us begin with the statutory requirements that have to be met in regard to the luminous distribution of the driving light. In most European countries these requirements are practically identical, but in the U.S.A. (and also in Great Britain) they differ somewhat. They can be illustrated by imagining a screen (*fig. 1*) set up at a distance of 10 metres in front of one headlight at right angles to its optical axis and indicating the illumination the light has to give at various points on that screen (*fig. 2*). In this diagram also a perspective image of a 6-m wide road is given, such as will be projected on the screen viewed from the headlight.

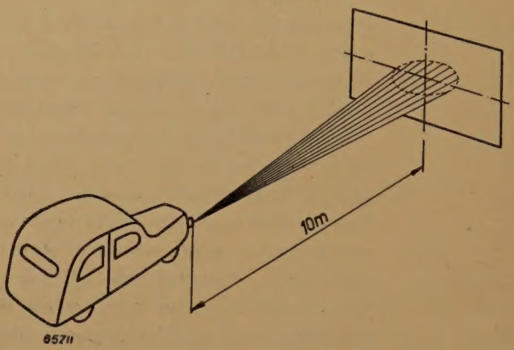

Fig. 1. To describe the property of a motorcar headlight the illumination can be shown in the points of a hypothetical screen placed at a distance of 10 m in front of a light at right angles to its optical axis. The point where this optical axis strikes the screen is the zero point of the system of coordinates drawn on the screen (see figs 2, 3, 5, 7).

From fig. 2 it is seen that American legislators have gone much further in giving details than their European colleagues in specifying the desired distribution of the driving light, but the minimum requirements for the centre of the beam do not differ much. In the directions corresponding, according to the perspective image, to parts of the road at a distance of say 150 m, levels of illumination of 100 to 200 lux are required on the 10-m screen, corresponding to about $\frac{1}{2}$ to 1 lux per headlight at the actual distance, thus 1 to 2 lux for two lights (cf the rough calculation at the beginning of this article). The difference between the European and the American conceptions appears to lie mainly in the greater lateral spread of the beam required in the U.S.A. For practical purposes this difference is not of much consequence: also the European specifications guarantee that for normal road widths the motorist has a view of the whole width of his part of the road and also the opposite traffic lane, as well as certain strips on either side of the road (the latter is of importance with regard to the possibility of pedestrians or vehicles being about to come onto the road ahead).

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[1]) Terminology proposed by the Standardization Committees of Great Britain and the United States of America for the International Standard Organization.

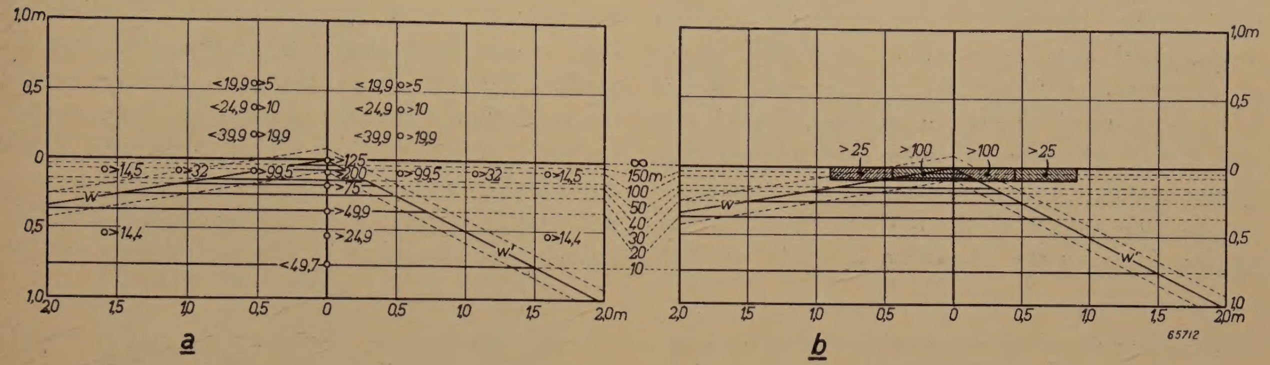

Fig. 2. Statutory requirements for driving light:
a) in the United States of America,
b) in European countries (excl. Great Britain).
The requirements are indicated by minimum or maximum values of illumination (in lux) at certain points (small circles marked respectively > or <) or within strips on the 10-m screen. The full lines *w*, *w'* are the perspective images of the left-hand and right-hand verges of the road, whilst also the projection of transverse lines on the road at different distances is indicated; the optical axis of the light is parallel to the road for these lines. The broken lines parallel to *w*, *w'* refer to the case where the optical axis of the lamp is tilted $\frac{1}{2}°$ upward or downward respectively.

There is a similar difference in respect to the vertical spread of the light. The requirements to be met are determined in the first place by the fact that the motorist must be able to see not only the parts of the road at a remote distance but, of course, also close by and, further, any objects which may be on or at the side of the road and which stand out above the horizon (trees, etc.). Moreover account has to be taken of the possibility of the optical axis of the headlight(s) — i.e. the axis of the beam of light — not being exactly horizontal but inclined a little upward or downward. The broken lines in figures 2*a* and 2*b* show how the road is projected on the coordinates of the 10-m screen when the angle of inclination of the lights is $\frac{1}{2}°$. Bearing in mind that the chassis of the motorcar is spring-suspended and thus while the car is travelling along the road the centre lines of the headlights will swing up and down due to the movement of the chassis, it is understandable that legislators have their reasons for paying attention also to the vertical spread of the light. Perhaps too little thought has been given to this in the European specifications, whilst the American requirements go somewhat beyond the mark and — according to European feelings — too much light is directed skyward.

Beam patterns and visibility distances

However this may be, in no respect do the American and the European specifications contradict each other as far as the driving light is concerned, so that it is possible for a certain type of light to answer both requirements. This is the case with the headlights commonly adopted in the U.S.A., the so called "sealed-beam" lamps (about which more will be said later). The European makes of headlights are more particularly adapted to European requirements, usually considerably exceeding the specified minima but not giving the wide lateral spread as required in the U.S.A. This is illustrated in *fig. 3*, where the beam patterns of two headlights have been given, i.e. the distribution of the illumination of the driving lights indicated by isolux lines on the above-mentioned 10-m screen. One headlight is an American sealed-beam lamp, while the other is a European make representative of the usual constructions on this continent. The much sharper focusing of the driving light from the European light is immediately noticed. To complete the comparison it may be stated that the axial luminous intensity of this European light fitted with a Philips "Duplo" bulb (for 6 V) is 60,000 cd as against 30,000 cd of the sealed-beam lamp, whilst the driving-light filament of the former consumes 35 W as against the latter's 45 W.

The extent to which a light answers its purpose can best be denoted directly by the visibility distance, i.e. the maximum distance at which an obstacle can with certainty be perceived under certain conditions. "With certainty" signifies here: at least in a certain percentage of all cases (this percentage can still be chosen somewhat arbitrarily, say 70 or 90%). With the very special distribution of the light and owing to the influence of incidental factors such as the dancing of the beam up and down, distraction of the driver's atteniton, etc., this visibility distance is difficult to derive from fundamental data of contrast sensitivity, speed of observation and suchlike. Consequently it has to be determined directly in an experimental way with the aid of test runs under standardized conditions matched to those occurring in actual practice ²). This applies all the more in respect to the passing lights, in the discussion of which we shall refer to the tests under driving conditions in more detail. As far as the driving light is concerned, suffice it to say that for the two types of lights of fig. 3 the visibility distances found during these test runs were 80 m (sealed-beam lamp) and 100 m (European light). These distances were the result of a large number of tests with two observers and different specimens of the two types of lights.

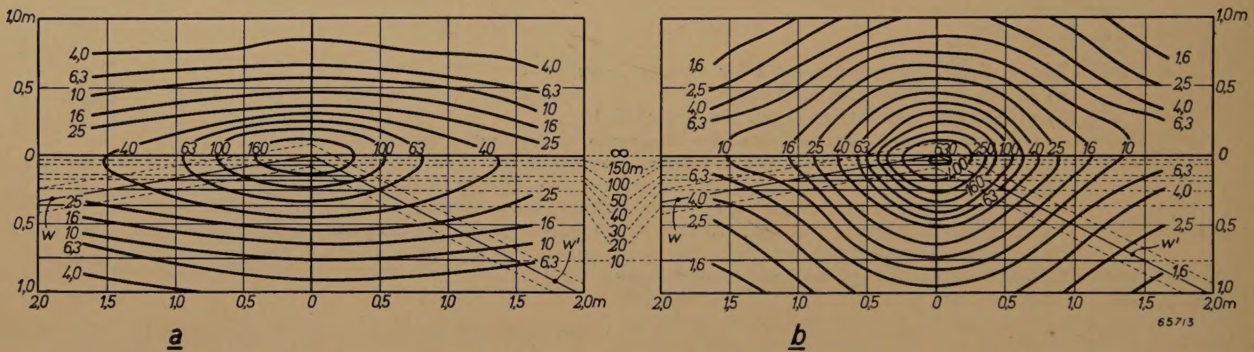

Fig. 3. Distribution of the driving light denoted by isolux lines on the 10-m screen (the lux values apply for a voltage of 6 V applied to the filament).
a) "Sealed-beam" lamp.
b) Bulb and headlight of European make.

Problems in the construction of the bulb and the headlight

How, it may be asked, are the beams of light represented in fig. 3 obtained? It would lead us too far afield to go into this question in every detail, but it is useful to touch upon the main points in the construction of the bulb and the headlight.

Typical and of importance for the construction of motorcar bulbs, of any type, is the low operating voltage from which one has to start, mostly 6 or 12 volts and in some cases 24 volts. This is related to the electric supply (dynamo with battery connected in parallel), but it is also the indicated voltage when considering the requirements that the bulbs have to meet. A certain minimum luminous intensity of the beam is desired within a certain solid angle determined by the spread required. This means that a certain luminous flux is needed, and to produce this with a not too great electrical power (no more than some tens of watts can be expended on each bulb) a type of bulb has to be used which has a high luminous efficiency (expressed in lumens per watt). A low voltage is favourable, for this implies a short and thick filament, which, for the same lifetime, can stand up to a higher operating temperature than a long and thin wire. Moreover a (coiled) short and thick wire gives a more compact filament, not only in itself (fewer turns) but more especially by reason of the fact that with a low voltage there is less danger from disruptive discharges in the gas with which the bulb is filled. Thanks to this compactness a sharply focused beam can be obtained with reflectors of moderate dimensions, so that little of the luminous flux is wasted outside the solid angle required ³).

The short, compact coil corresponding to the low voltage is likewise favourable for making the filament strong enough to withstand the shocks

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²) V. J. Roper and E. A. Howard, Seeing with motorcar headlamps, Ill. Eng. **33**, 417, 1938; V. J. Roper and K. D. Scott, Silhouette seeing with motorcar headlamps, Ill. Eng. **34**, 1073, 1939; H. H. Magdsick, Some factors governing visibility distance with motorcar headlights, Annex to Report No. 23b, I.C.I. 1939.

³) Further, the low voltage enables practically pure argon to be used for the filling of the bulb (thus without the addition of nitrogen which is necesssary for normal incandescent lamps so as to raise the disruptive voltage of the gas), so that the permissible temperature is raised and thus the luminous efficiency increased. Use is made of this in the 6-V bulbs.

and vibrations to which it is subjected when the car is travelling along bad roads or when the car is badly sprung. In passing it may be noted that this combination of shocks and vibrations is particularly serious and has constituted a difficult problem for the makers of motorcar bulbs. *Fig. 4*, illustrating a Philips motorcar bulb (of a type with only one filament), shows the shape of the filament and the supporting "mount" giving the necessary strength to the bulb. This bulb gives a total luminous flux of 640 lumens for a consumption of 35 watts.

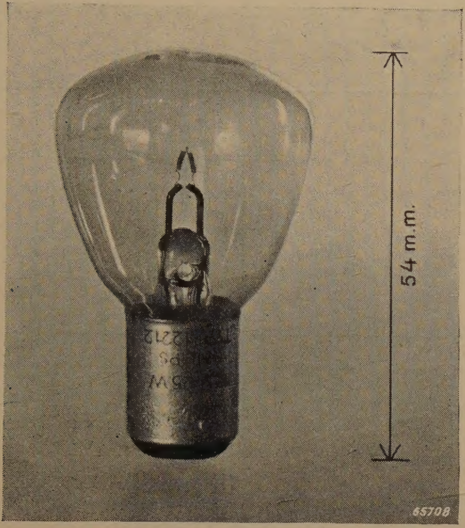

Fig. 4. Philips bulb with one filament, type 12212, for motorcar headlights.

The bulb illustrated in fig. 4 is placed in a headlight containing a parabolic reflector, in such a way that the filament coincides with the focal point. Ribs on the envelope of the bulb, on the front glass of the headlight or on the reflector itself — there are various makes, with no essential differences in the optical sense — together with the suitably chosen shape, dimensions and position of the filament ensure the right luminous distribution of the beam emitted. Owing to its sturdy construction the filament is kept accurately in position while the car is travelling along and bulbs which have been used for quite a long time still show this property.

Of course it is of great importance that when a new bulb is fitted into a headlight its filament comes to lie exactly in the right position. This is ensured by a pre-focusing of the filament in the factory with the aid of a special adjusting device [4]) by means of which the filament is given a very accurately determined position with respect to a pair of studs, stops or suchlike provided on the base of the bulb. These studs in turn determine the possition of the base in the holder, and thus within a very narrow tolerance the position of the filament in the reflector. There are numerous modifications of this principle (see, e.g., fig. 9).

Following upon this prefocusing system, it is useful to say something about the sealed-beam lamps already mentioned (see below, fig. 8). Here the intermediate link in the form of studs, etc. is dispensed with and the reflector and bulb are made into one unit, the bulb being cemented or soldered into the reflector with the aid of an adjusting device. When the bulb has burnt out both the bulb and the reflector have to be replaced by a new unit (i.e. the so-called metal-package sealed-beam). One has even gone a step farther in producing the all-glass sealed-beam lamp, in which the filament is mounted in a vacuum-sealed reflector. An advantage of both these constructions is that the problem how to exclude dust and dirt from the inside of the lamp is thereby completely solved.

The typical difference in the luminous distribution as between American and European headlights is not, however, at all correlated with the constructional differences described here. A lamp of the sealed-beam design could, in principle, be made with a European beam pattern, and vice versa.

The passing light

Statutory requirements and beam patterns

In dealing with the passing light it is again convenient to start from the statutory requirements for the luminous distribution. These are denoted on the 10-m screen in *figures 5a* and *5b*, where in addition to the perspective image of the road also the projection p is given of the line along which the eye of the driver of an oncoming car moves in a situation as shown in *fig. 6* (the dotted lines again apply for the case where the headlight is inclined $\frac{1}{2}°$ upward or downward). From these diagrams it should be possible to decide what value of the illumination on the eye of the oncoming driver and therefore also on one's own eye in various situations is to be tolerated by law. Strangely enough, however, neither the American nor the European legislators say anything about this point (or rather about this line). From a comparison of figures *5a* and *5b* it can only be concluded that in directions approaching the horizontal the European lights are bound to much lower maxima than the American ones. Further it is seen that the American law stipulates that at a short distance (about 40 m) the passing light has to throw more light on the right than on the left side of the road, with a much higher minimum for the right half than is required in Europe (for the right as well as the left). For the parts of the road at distances of 50 to 100 m, which as far as observation with the passing light is concerned are much more important than distances less than 50 m, neither in America nor in Europe is any minimum illumination prescribed — again a striking omission.

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[4]) See also: Th. J. J. A. Manders, Incandescent lamps for film projection, Philips Techn. Rev. 8, 72, 1946.

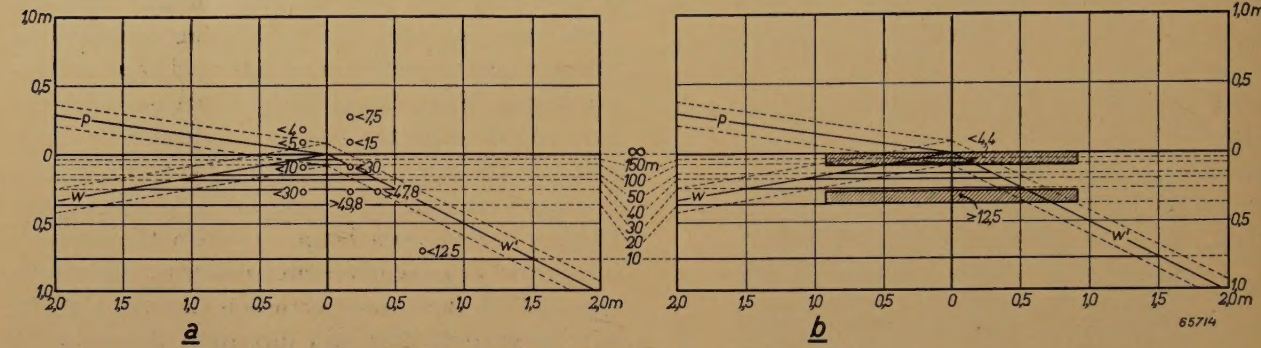

Fig. 5. Statutory requirements for passing light,
a) in the United States of America,
b) in the European countries (excl. Great Britain).
In addition to the perspective image of the road (lines *w* and *w'*), also the projection *p* is shown of the line along which the eye of an oncoming driver moves when the two cars are travelling in the middle of their own lanes on a road 6 m wide (see fig. 6). The broken lines parallel to *p* refer to the case where the headlight is tilted $\frac{1}{2}$° upward or downward.

The differences between the regulations are reflected quite clearly in the actual beam patterns of the passing light used in American and in European headlights; see *fig. 7*. In the European light the beam is sharply cut off a little below the horizon, whilst in the American light there is asymmetry of the passing light and a comparatively gradual fall round about the horizon. The latter fact results in a much stronger glare from the oncoming car than is the case with the European light.

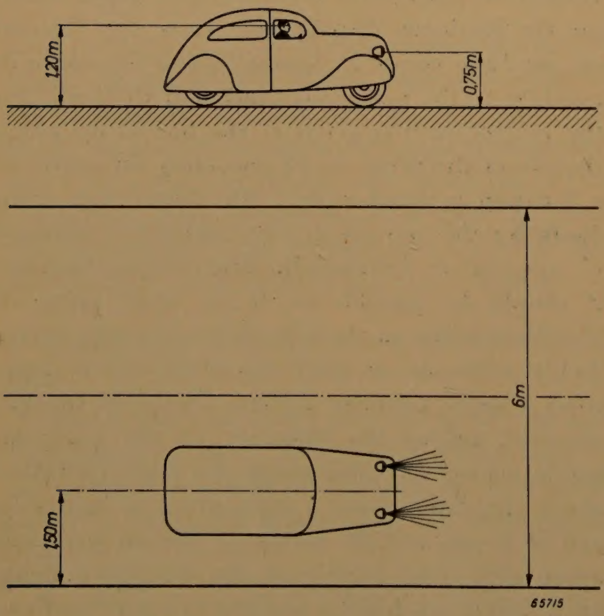

Fig. 6. Situation of an oncoming car where the driver's eye moves along a line projected from the light in line *p* on the 10-m screen of fig. 5.

The asymmetry of the American passing light has the obvious disadvantage that when a car is coming round a bend to the left a great deal of light is thrown to the side of the road. What, then, is the reason for prescribing this asymmetry? An explanation is to be found in the remark that there is not only a bad but also a good side to the appearance of an oncoming car: two pairs of headlights then illuminate the road between the two cars. It is then obvious that each car can provide especially for the illumination of its own traffic lane, lighting this part of the road to a high level, higher than with the European system, and leave the illumination of the other lane mainly to the other car. Unfortunately in putting this idea into effect so much light is "wasted" that the advantage of the more favourable lighting of the road is at least for the greater part lost owing to the relatively stronger glare. The question whether and in how far there is any advantage left (or a disadvantage) has formed the centre of a discussion which will be dealt with presently. The difference in the two systems may be further illustrated by *table I*, showing more accurately than in fig. 7 the levels of illumination produced by the American and the European lights at various distances (a) on the road (in the middle of one's own traffic lane), and (b) on the eye of the driver of an oncoming car. For a distance of 100 m the glare and the illumination from the American passing light appear

Table I. Illumination, in lux, obtained with American and European passing lights (two headlights) at different distances between passing cars.

Distance from oncoming car in metres	American system		European system	
	on vertical object in middle of own lane beside oncoming car	on eye of driver of oncoming car	on vertical object in middle of own lane beside oncoming car	on eye of driver of oncoming car
200	—	0.04	—	0.014
150	0.18	—	0.04	—
100	0.6	0.12	0.16	0.04
50	4	0.3	3	0.1
30	—	0.6	—	0.2

away than the filament for the driving light. Furthermore this small coil is contained in a small, spoon-shaped cap. This form of mounting brings about the illustrated sharp cutt-off of the beam. At the same time the cap reflects the screened-off light, so that part of this at least can still be utilized. Special attention is drawn to the insulated arm connecting one of the poles to the end of the cap supported by an extra rod, thus giving this construction the necessary mechanical strength.

Comparison of the American and the European systems

The question whether two such widely different kinds of passing light both yield satisfactory results is to be answered in the affirmative, at least in so far as countries are concerned where either the one or the other system is exclusively used. Shortly after the second world war, however, there was such a dire shortage of cars in Europe that a great many American cars had to be imported and — as has been the case with all American cars since 1939/1940 — these were equipped with sealed-beam lamps. When passing one of these American cars on the road at night the driver of a European car having the headlights common to this continent was at a disadvantage, being subjected glare from the American light, whereas the driver of the American car experienced much less trouble from glare and, moreover, found his traffic lane more brightly illuminated. This difference can be seen from table I: for the driver of the American car there were the illumination levels of the two outermost columns, while the driver of the European car had those in the two innermost columns. The ratio of the illumination on the road beside the other car compared with that on the driver's own eye at 100 metres distance was 15 for the driver of

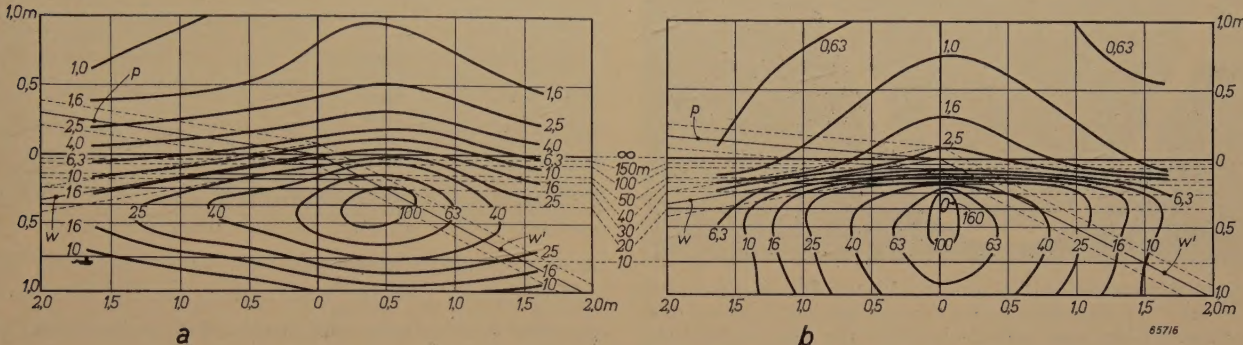

Fig. 7. Distribution of the passing light denoted by isolux lines on the 10-m screen (filament voltage 6 V).
a) Sealed-beam lamp.
b) Bulb and headlight of European type.

to be stronger by about the same factor than the levels of the European lights (assuming that the glare effect may be taken as being proportional to the illumination on the eye); for a distance of 50 m however the glare is three times and the illumination only 1.3 times as strong as that of the European passing light.

Constructional details

The manner in which the two so greatly different types of passing light are obtained can be roughly explained with the aid of *figures 8* and *9*. In the sealed-beam lamps (fig. 8) a separate filament for the passing light is placed slightly above the axis of the parabolic reflector and a little to the left (as viewed from the driver's seat) of the filament for the driving light, so that the beam of light is directed more downward and more to the right. In fig. 9 we see the Philips "Duplo" bulb type No. 6725, with which the beam pattern of fig. 7*b* was obtained. Here the filament for the passing light consists of a straight coil lying practically in the axis of the parabolic reflector but placed farther the American car and 1.3 for the driver of the European car!

Discussions therefore inevitably arose on the question which of the two systems was the better and thus which of the two should make place for the other in order to avoid the drivers of European cars being placed at such a disadvantage. This matter received the attention of the congress of the International Committee on Illumination held in Paris in 1948. Here we can only briefly outline the controversy, which is still not solved.

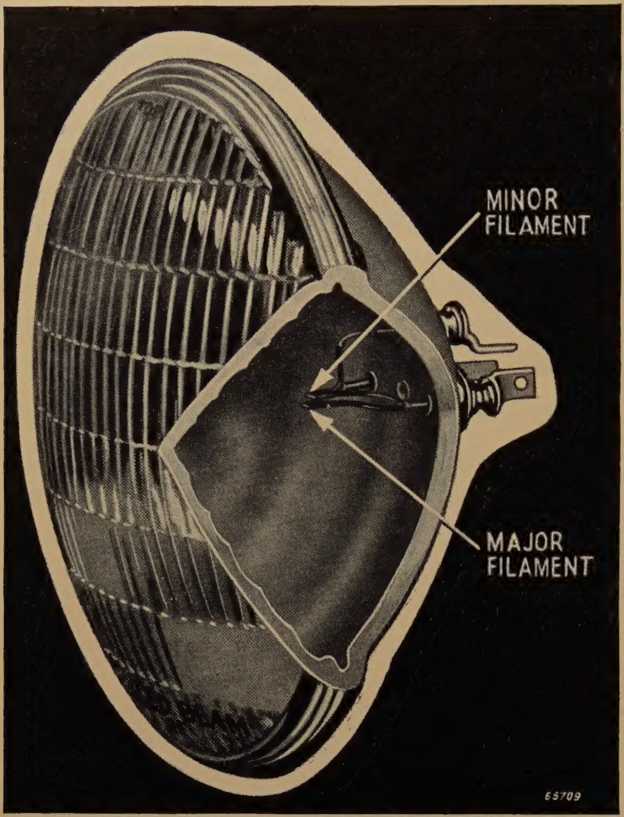

Fig. 8. All-glass sealed-beam lamp with two filaments (General Electric Co.). The filament for the passing light is above that for the driving light and displaced to the side, so that the reflector throws the light mainly onto the right-hand half of the road. The lamp bulb has not a separate, cemented-on base but three pins fused into the glass. A contact plug can be fixed on these pins. The bulb, moulded in the form of a paraboloid, is lined on the inside with a reflecting layer. (Taken from H.H. Magdsick, Ill. Eng. **35**, 537, 1940.)

Determining the visibility distances

An impartial comparison of the two kinds of passing light will have to be based upon experimentally determined visibility distances, as previously indicated. Compared with those for determining the driving light, however, these experiments are more complicated, since when two cars are passing the visibility distance changes owing to the glare from the oncoming car gradually increasing during the approach and then, after passing, rather quickly disappearing (not abruptly, because the eye needs some time for re-adaptation).

Magdsick, Roper and others carried out such experiments (see the articles quoted in footnote [2]) already in 1938, both with the European system established since about 1930 and with the American system which in 1938 was still in course of development. As objects which had to be observed, Roper

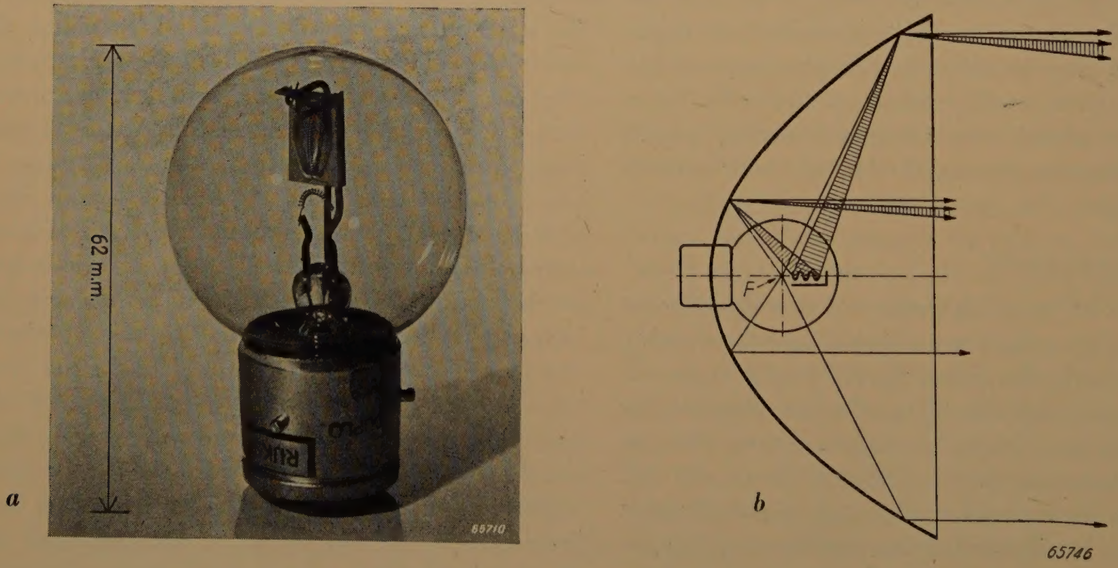

Fig. 9. *a*) Philips "Duplo" bulb, type No. 6725. On the base can be seen two of the three studs with which the lamp is focused: they ensure that the axis of the lamp coincides with that of the reflector, the filament being "prefocused" with respect to the studs. The filament for the passing light is in a spoon-shaped cap almost in the axis of the parabolic reflector in which the lamp is placed but farther away than the filament F for the driving light (*b*). With this arrangement the beam of the passing light is cut off fairly sharp just below the horizontal (fig. 7*b*): the cap ensures that no rays fall upon the lower half of the reflector, which would otherwise be reflected in a somewhat upward direction.

used life-size dummies set out on the right-hand half [5]) of the road (50 cm from the verge, on a road 6 m wide). Although these experiments yielded very instructive results, in our opinion the basic conditions were not very aptly chosen. With life-size dummies there is a good chance of the upper part of them being observed from a great distance owing to the silhouette effect, which Roper first remarked upon and which is to be seen in *fig. 10*. But as the lower part of the dummy cannot be distinguished the motorist cannot judge its distance, and this is essential for deciding what action to take (swerving aside or braking). Moreover in this phase of passing a low obstacle on the road in the same position as the dummy would certainly not be noticed. Another point is that objects on the right-hand side of the traffic lane are not the most difficult to observe; with objects on the left-hand side of the traffic lane the adverse influence of glare is felt more strongly.

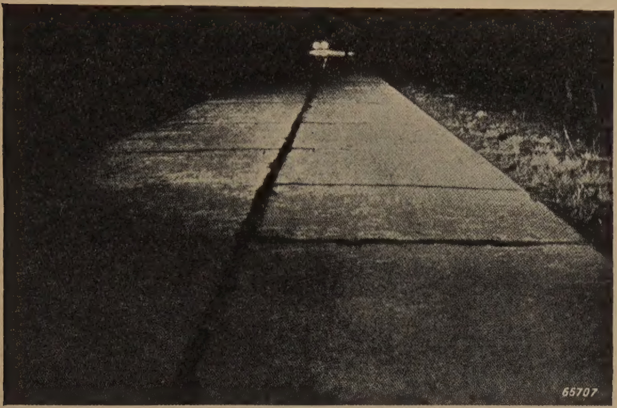

Fig. 10. When two cars are about to pass, a tall object on the right-hand side of the lane can sometimes be observed from a great distance owing to it standing out as a silhouette against the patch of light thrown on the road by the oncoming car. (Taken from V. J. Roper, Ill. Eng. **34**, 1073, 1939.)

This criticism of Roper's basic conditions has been supported by a series of tests carried out with a stationary set-up [6]) using as objects eight moveable columns placed at equal intervals over the width of the whole road (in our case 16 m). Variations were made firstly in the distance of the oncoming car, secondly in the distance of the row of columns for each "oncoming car" distance, and thirdly in the height of the columns (22, 44, 88 or 176 cm). Measurements were taken by asking two trained observers to give the degree of visibility according to a scale of 5 steps from "invisible" to "strikingly noticeable". When all the points on the road found to have the same degree of visibility, with the oncoming headlight in a fixed position, are connected by a line we get a plan which, when plotted for different systems of headlights, permits of a comparison of their qualities. In *fig. 11* we have by way of example a series of ground plans plotted from a large number of observations for an "oncoming car" at a distance of 200 m. It is clearly seen that in this case the results with the European passing light and with object heights of 22 and 44 cm are somewhat better than those obtained with the American passing light, whereas a marked difference in favour of the American system is only found with tall objects on the extreme right of the road — exactly the conditions considered by Roper and his cooperators!

Taking as basis less tall test objects — and we believe that this is desirable — we find from the stationary tests practically equal visibility distances — also with the oncoming car at other distances

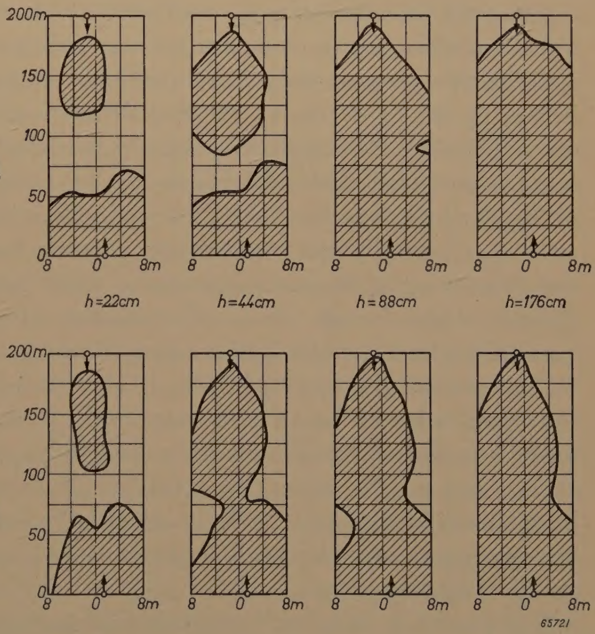

Fig. 11. Visibility distances found from tests with stationary cars placed as if they were passing each other on a road 16 m wide at a mutual distance of 200 m. The arrows denote the position and the direction of the light from the headlights. The tests were carried out with objects of four different heights *h*, with the passing light of American (*a*) and of European (*b*) lights with distribution of light according to figures 7*a* and 7*b*. The lines connect the points on the road where an object was given a degree of visibility "$1\frac{1}{2}$". The scale used for the degrees of visibility was: 0 = invisible, 1 = doubtful visibility, 2 = visible with difficulty, 3 = easily visible, 4 = strikingly visible. The hatched areas are those of at least just sufficient visibility.

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[5]) In the work of Roper and others, as also in this article (fig. 2), it is assumed that cars are travelling on the right-hand side of the road, as is the rule in most countries of the world.

[6]) A report on these tests was submitted to the Paris congress of the I.C.I., viz: J. B. de Boer and D. Vermeulen, On measuring the visibility with motorcar headlighting, Congress I.C.I., Paris 1948, Appl. Sci. Res. **B2**, 1-32, 1951 (No. 1).

— for the American and for the European passing light, with a slight advantage for the latter, as illustrated by *fig. 12.*

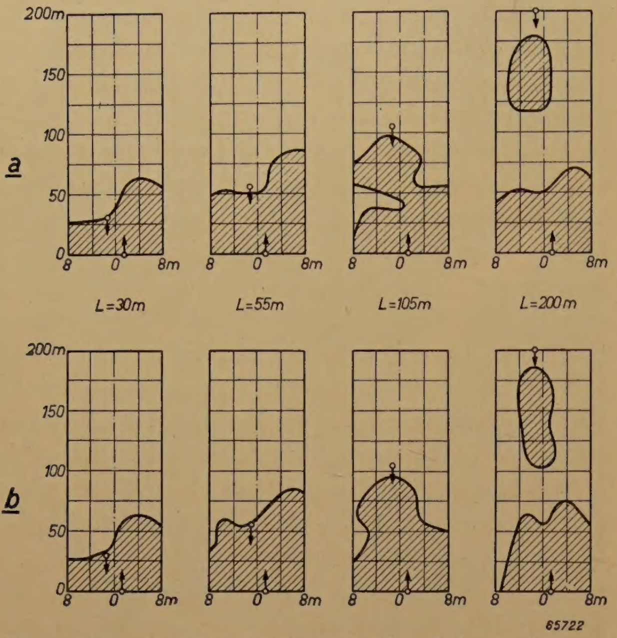

Fig. 12. The same as fig. 11 but with four different distances L between the cars; all these tests were taken with an object height $h = 22$ cm.

Although in our opinion stationary tests are quite suitable for a comparative investigation, and for this purpose they have also been applied in fact by the I.C.I., for an absolute determination of visibility distances the I.C.I. thought it advisable to carry out tests under driving conditions as well, as **Roper** had done but taking our objections into account. Naturally the organisation of such tests and the taking of the measurements is much more difficult than in the case of stationary tests, especially where the aim is to get results which can be internationally accepted. The I.C.I. entrusted the organisation of these driving tests to the Netherlands Foundation for Illumination, and they were carried out on the car-racing track at Zandvoort in Holland in October 1949, in accordance with directives given by the I.C.I. Committee on Automobile Lighting.

Unfortunately the Zandvoort trials did not yield any valuable results, owing to the fact that the measurements of the beam patterns of the French headlights used for the European passing light proved that they were not at all representative of the European lamps. Therefore no results of these trials will be reported here, but instead we shall give the results of driving tests carried out six months earlier by the Light-technical Laboratory of Philips at Eindhoven, which were almost entirely on the same lines as laid down by the I.C.I. for the Zandvoort trials. In particular, this implied that all conditions had to be very carefully defined and fixed. For instance, the reflection of the road surface was investigated, small irregularities in the longitudinal profile of the road were measured, the adjustment of the headlights on the two cars used was carefully checked with a special device, the beam patterns of all the combinations of headlights and bulbs used were determined, the supply voltage for the bulbs was kept highly constant and checked with the aid of calibrated voltmeters, the observers' eyes were tested in an oculistic clinic, etc.

The measuring procedure and the manner in which the results were analysed will be dealt with more fully in an appendix to this article. As to the analysis of the results, we would only point out here that there was considerable spread in the values found for the visibility distance, as is understandable. One of the most important problems in such an investigation is how to distil from the widely spread measuring results a nucleus of real differences (in so far as there are any!) [7]).

Our tests differed from the international ones only in so far that ours were limited to low test objects 22 cm high, whereas at Zandvoort tall and low test objects were used (1.50 m and 40 cm). They were carried out on two roads, a rather rough one near the Eindhoven airport and a smooth concrete road near Meteren (Netherlands). There were no systematic differences between the results on the two roads, so that they could all be used for the common purpose. The results finally worked out have been plotted graphically in *figures 13* and *14*, showing the visibility distance V as a function of the distance L between the two cars, (a) for the American passing light, (b) for the European passing light, with objects placed on the right of the road (fig. 13) and with objects placed in the centre of the road (fig. 14). Negative values of L correspond to the situation where the two cars have already passed each other, and it is then seen how the eye more or less gradually readapts itself after the glare. This visual recovery actually begins even earlier, when the cars have approached each other to within 50 - 100 m: the glaring headlights of the oncoming car have then moved a good way towards the periphery of the field of vision, where the glare effect is less. In the case where the object is on the right of the road (fig. 13) the American passing light shows a slight superiority compared with the European, but where an object is in the middle of the road (fig. 14) the European passing light proves to be somewhat better just in the most critical phase of passing. The curves in figs 13 and 14 are based upon the measurements given by six observers with normal eyesight, and each curve is based on 70 to 80 measured points.

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[7]) The measuring procedure, the check measurements and the method of analysis, together with the results of the Zandvoort trials, are described in an extensive report submitted by the Netherlands Foundation for Illumination for the Congress of the Committee on Automobile Lighting of the I.C.I. at Turin in 1950.

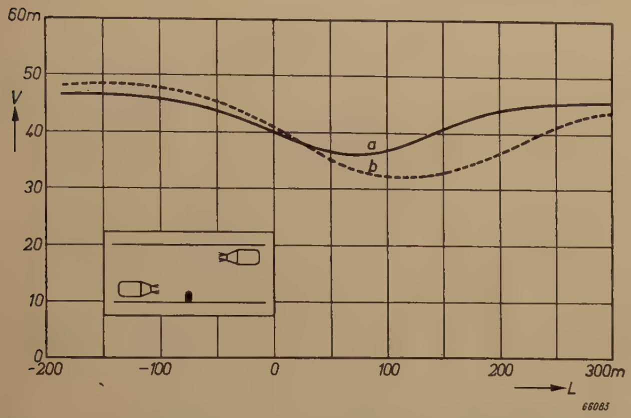

Fig. 13. Visibility distance V (defined by: observation in 50% of all cases) measured during tests with travelling cars on the Eindhoven airport and on a state highway at Meteren (Netherlands), for the passing light of American (a) and European (b) lights with luminous distributions according to figs. 7a and 7b. V has been plotted as a function of the "oncoming-car" distance L. The curves apply for an object 22 cm high placed on the right of the traffic lane.

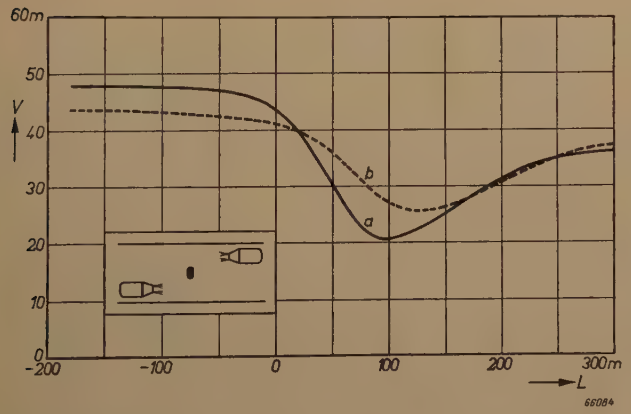

Fig. 14. The same as fig. 13 but for an object placed in the centre of the road.

Although from the results of these tests we ourselves believe that the European system is certainly not inferior to the American, the controversy between the two schools of thought in automobile lighting is still unsettled owing to the failure of the Zandvoort trials. We shall have to await further developments (the possibility of repeating the trials is being considered), but meanwhile the curves in figs 13 and 14 permit of a final general comment.

Other solutions of the problem of the oncoming vehicle

When we pay particular attention to the minimum of the curves in figures 13 and 14 we see that the visibility distances (for low objects) are not greater than 20 to 35 m. This means that one can only see past the oncoming car when this has approached within a very short distance (much shorter than the braking distance of a car). (Such an effect is also clearly seen in fig. 12.) This is the well-known phenomenon where a motorist, in passing another car, gets the feeling for a moment that he is driving into a black patch and has to trust to his lucky stars not to crash into something at that critical moment.

Motorists have grown accustomed to this hiatus in the safety measures and, so long as this "passing' situation does not occur at too great a frequency and drivers refrain from passing each other at top speed, there seems to be no cause for great anxiety. The position is different, however, on busy parts of highroads where during the peak hours there is an almost continuous line of cars passing. One is then obliged to drive practically all the way with only the passing lights on, and speed has to be reduced to 60 km/hr or less so as to adapt the braking distance to the visibility distance. To avoid this necessity of reducing speed the best solution is to illuminate such roads with sodium lamps (as has already been done for several highroads), for then the headlights can be switched off and all cars can travel safely with only the side lights on.

There are some other interesting, and more universal, possibilities of solving the problem of the oncoming vehicle. In the first place there is the use of linear or circular polarised light, already tried out in practice. When the light from the headlights of all cars is circular-polarised in a clockwise direction for instance, by means of a polariser and a $\frac{1}{4}\,\lambda$ foil placed in front, and the same foils are placed on the wind screen of the car, the driver can see the light from his own headlights even though it is partly depolarised in the reflection on the road. The light from the headlights of the oncoming car, however, is "seen" to be circular-polarised in an anti-clockwise direction, so that it is not really seen at all (or almost not, since owing to the dispersion the extinction is not complete for all wavelengths). There is then no longer any need to switch over to the "passing" light and one can drive on with the driving light [8]). The fact that this excellent solution has not yet been adopted is due mainly to the inevitable loss of light that the polarisation entails. Theoretically at most one-third but practically still less of the luminous flux from the lights is utilized, so that the headlights would consume much more electric power than they do at present.

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[8]) Among the extensive literature on this special subject there are to be mentioned a review by W. Christoph and H. E. J. Neugebauer, Z. techn. Phys. **20**, 257-264, 1939, and three reports of a more recent date: E. H. Land, J. H. Hunt, V. J. Roper, Bull. No. 11 Highway Research Board, June 1948.

This objection could be overcome by arranging for the driving light to be polarised not permanently but only while passing other vehicles, for instance by means of louvre-like foils being tipped downward in front of the lights and the wind screen. At the same time it should then be possible to switch over to another higher-powered filament for the driving light, thus compensating the loss of light in the foils by a momentary overloading of the battery.

Another suggestion for solving the glare problem is to dispense with the use of permanently burning headlights and to install in their place flashlamps giving periodically — say with a frequency of 50 c/s — extremely short and intensive beams of light lasting, for example, 1/10,000 sec. The eye then sees the road just as well as if it were continuously illuminated by an incandescent lamp of the same total luminous flux (apart from possible stroboscopic effects, which may make a higher frequency necessary), but it is then possible to screen off the driver's eyes, for instance by means of a rotating shutter, in the periods during which the headlights from his own car are not emitting any light. Since these periods, in the given example, cover $99\frac{1}{2}\%$ of the whole time, the intensity with which permanently burning "foreign" light sources (e.g. of an oncoming car) are observed would be reduced to 1/200th [9]). This system has not yet been tried out in practice.

Appendix: Measuring procedure and method of analysis adopted for the driving tests

Fig. 15 is a diagrammatic representation of the road along which the trials were carried out. Two cars started simultaneously from the fixed starting points A and A'. The speed had to be uniformly increased so that the cars reached the points B and B' almost at the same moment, and from that point onward they had to travel at a constant speed of 64 km/hr. Upon reaching the points C and C' the drivers had to switch over from driving light to passing light. An object was placed on the road at a variable point between C and C'. The moment that a driver saw the obstacle he set a distance meter into action and stopped it as soon as he reached the obstacle (an assistant pulled the obstacle off the road just before the car reached it). In this way the distance from observer to object — thus the visibility distance V — was measured.

It was required to find the visibility distance as a function of the distance L between the two cars. Typical of the tests described (and also of other tests, such as **Roper's**) is the fact that the "independent variable" L is uncontrollable.

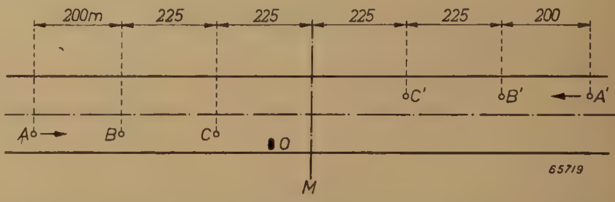

Fig. 15. Simplified driving diagram of the tests with travelling cars. The two cars started simultaneously at A and A' with driving lights on, accelerating speed up to 64 km/hr, which speed should be reached at B and B', and switching over to passing light at C and C'. O is an object that had to be perceived.

The value of L at the moment the object was observed can be deduced only from the measured value V of the visibility distance after the test has been carried out, and this is done in the following way. One starts from the assumption that from the moment that both cars have reached a constant speed they travel exactly symmetrically with respect to the point where they meet. This point is determined by one or more assistants standing along the road. If it lies at the distance P from the middle of the whole length of road travelled and the object is placed at a distance D ("object eccentricity") from that middle point, then (see *fig. 16*) apparently:

$$L = 2\,(V + D - P) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

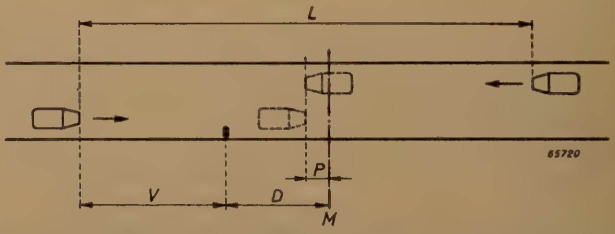

Fig. 16. The objects were placed at different distances D from the middle M of the length of the road travelled. The two cars do not as a rule meet precisely in the middle M but at a short distance P from it. From D, P and the visibility distance V it is possible to calculate the distance L between the cars at the instant the object is observed.

Suppose that for the same value of D—P a number of different visibility distances V have been recorded by different observers. These values will then have to be averaged or, to be in agreement with the definition previously given, one has to find what value is exceeded in 70% or 90% of the observations, and from the value thus found, V_0, the corresponding L_0 has to be calculated with the aid of equation (1). In this way one point of the $V(L)$ curve is determined. It is true that in practice this is not quite so simple, since owing to discrepancies in the value of P there is hardly ever a series of, nor even two, measuring points with exactly the same value of the "independent variable" D—P. But it can nevertheless be done indirectly: the measured values of V are plotted as a function of D—P and this diagram is covered with a vertical strip of a certain width. The abscisse value $D - P$ of the middle of the strip is then given, for instance, an ordinate value V_1 corresponding to that measuring point which is the next lowest above 30% of all the measuring points covered by the strip. When this has been carried out for all possible positions of the strip, the curve $V_1 = f(D - P)$ can be drawn. This indicates the distances for a 70% chance of perception and serves as a criterion for judging the passing light in question. In the same way, of course, a line can be constructed say for 90% or 50% chance of perception.

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[9]) A system of phase-control of the flashes might be desirable to avoid trouble being experienced from a passing car having the same system with, by chance, exactly the same frequency. — The idea of very short flashes synchronized with a shutter may likewise be of importance for signalling systems where it is desired to eliminate the effect of disturbing background lighting (e.g. daylight) when receiving light signals (e.g. from ground lights of an airport).

Remarkably enough, for the driving tests previously carried out neither this nor any analogous method of analysis has been applied, but a method which subsequently proved to be erroneous: for each measured value of V one proceeded at once to calculate the passing-car distance L according to eq. (1) and then plotted all the V values as functions of L (*fig. 17*); then the method of vertical strips (or something similar) was applied to the diagram. The fault of this method lies in the fact that for a given value of L an average is taken from V values obtained with different object positions D, and thus under different conditions. The consequences of this are evident from the following. If we assume, for the sake of simplicity, that for all runs $P = 0$, then for each run $V = \frac{1}{2}L - D$, and all measuring points for runs with a certain chosen value of D would come to lie along one of the oblique lines in fig. 17, statistically distributed along it (Gauss' law of distribution). In the area of large "oncoming-car" distances, $L > 200$ m, the method of working with vertical strips will now undoubtedly yield too high values for V owing to the law of distribution in the vertical strip being unilaterally influenced: no low V values can be found in the vertical strip because there have been no tests with a sufficiently great object eccentricity D! Similarly, in the area on the extreme left of the graph one certainly finds too low V values.

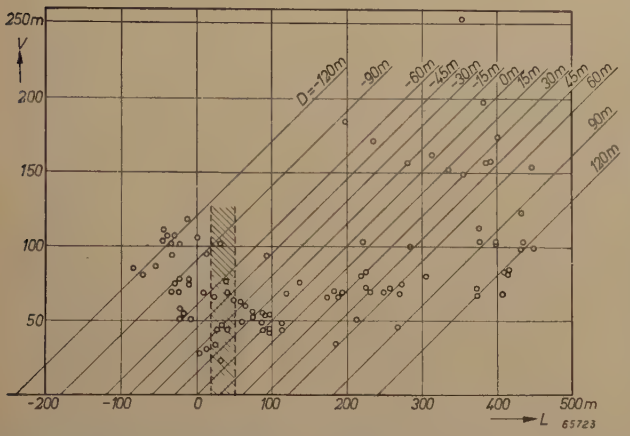
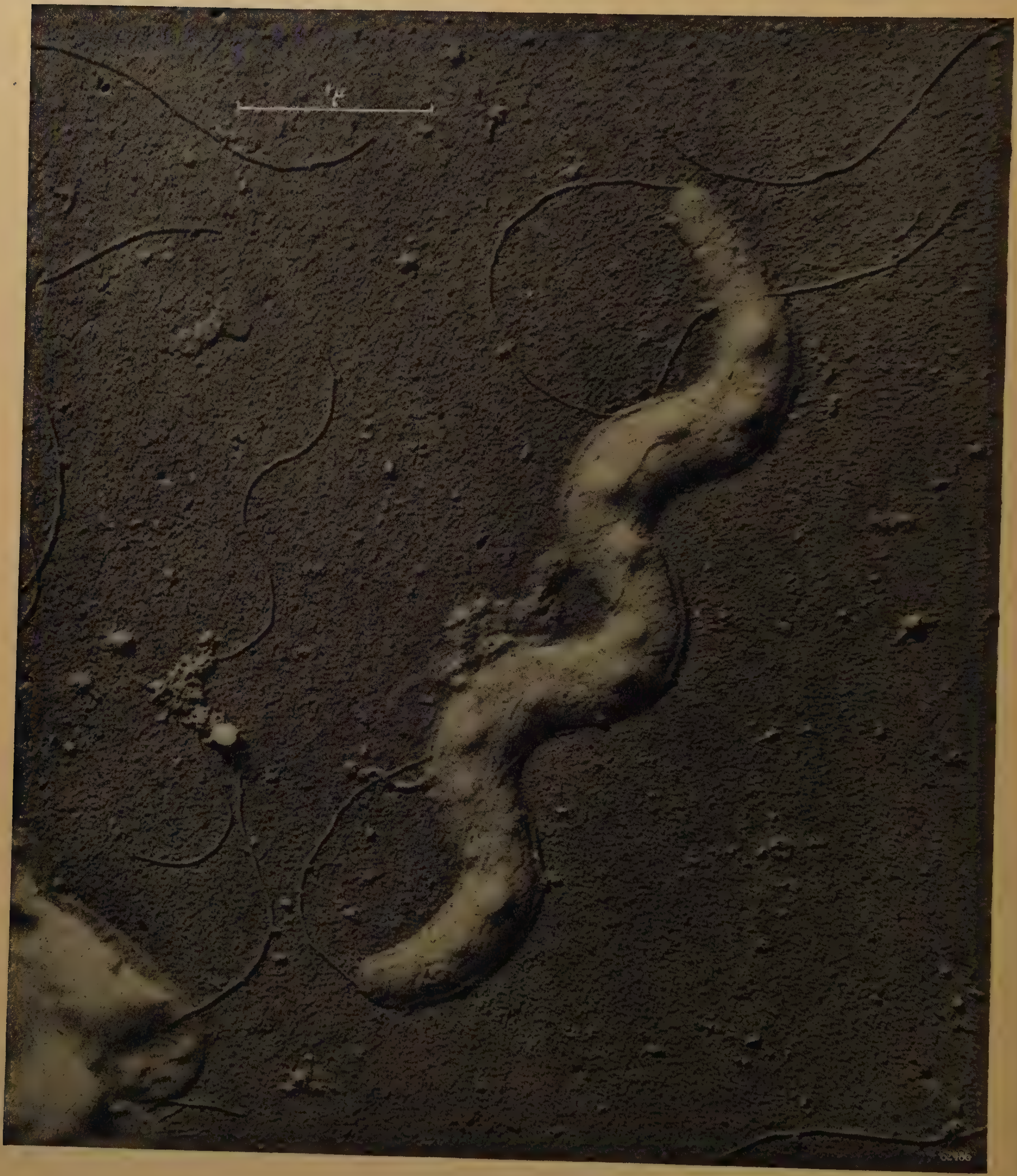


Fig. 17. Diagram explaining the method by which the "averaged" visibility distances V as function of L can be derived from the widely spread measuring results.

It is therefore essential first to work out the relation between V and $D - P$ and then to plot this in a (V, L) graph. It is in this way that figures 13 and 14 have been constructed.

Summary: The driving light, used by a motorist when normally travelling along the road in the dark, and the passing light, to which he switches over when approaching a vehicle coming from the other direction, both have to satisfy statutory requirements in order to ensure certain minimum visibility distances and not to cause excessive glare when passing the other vehicle. The American specifications differ from those in Europe. In this article both the requirements and the actual distribution of light are graphically illustrated for the driving light and for the passing light according to the American and the European systems. The two systems are compared and some typical details of the construction of European bulbs (Philips "Duplo" bulb) and American "sealed beam" lamps are discussed. Although in several respects the statutory requirements are to be regarded as incomplete, both the European and the American systems yield satisfactory results, except at the moment immediately before passing another vehicle, for which situation there is a hiatus in the safety measures. But also apart from this, difficulties are apt to arise in the case where American and European headlights are used on the same road. In that case the motorist with European headlights on his car is greatly at a disadvantage as far as visibility is concerned. The discussions arising therefrom at the congress of the I.C.I. held in Paris in 1948 led to a repetition of the tests for directly determining visibility distances. Such tests have been carried out under stationary and under driving conditions by Philips Light-Technical Laboratory at Eindhoven, and under the auspices of the Netherlands Foundation for Illumination stationary and driving tests were likewise carried out especially for the I.C.I. at Zandvoort (Netherlands) in October 1949. Although the controversy between the American and the European schools of thought has not yet been definitely solved by these tests, the results — both of the stationary and of the driving tests — indicate that neither the one nor the other system can be regarded as being markedly superior. An interesting question related to these trials is how to analyze the widely spread results obtained from the measurements. An improved method for this is described in an appendix.

A BACTERIUM MAGNIFIED 33000 TIMES



Photograph taken with the Philips electron-microscope for 100 kV. According to its shape this bacterium belongs to the Spirillum group. It is found in water and is not morbific. The specimen has been shadowed by precipitation of an alloy of gold and palladium, thereby accentuating the relief structure of the somewhat dried-out cell. A flagellum is seen at both ends.

THE ELECTRO-ANALOGUE, AN APPARATUS FOR STUDYING REGULATING SYSTEMS

II. THE ELECTRICAL EXECUTION

by J. M. L. JANSSEN and L. ENSING.

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The electro-analogue is a type of calculating machine specially designed for studying regulating systems. Its action is for the greater part electronic, just like that of the calculating machines destined for more universal use, a known example of which is the "ENIAC". Whilst the latter has no less than 18,000 electronic valves, in the electro-analogue described below 350 valves are used.

The name of **electro-analogue** is used for a collection of parts with which electrical models of automatic controllers can be built and their action studied. The component parts and the use of such an electro-analogue have been discussed in broad lines in a previous article [1]). In what follows the electric circuits will be dealt with in more detail.

In *fig. 1* the (incomplete) block diagram of the electro-analogue is reproduced for ready reference. The principal parts are:

1) the **process analogue** P', a network whose step-function response can be made identical with that of a process that is to be studied;
2) the model of a **continuously acting controller**, comprising an amplifier A, a proportional, an integrating and a differentiating element, and also the variable attenuators Z_0, Z_a, Z_b and Z_c (in this model there is also a second integrating and a second differentiating element, not drawn in fig. 1);
3) some **models of discontinuously acting controllers** (not drawn);
4) a **collecting stage** S_1, in which the output voltage(s) of the controller and a periodically repeated voltage step, which it is possible to introduce as a disturbance, are added together;
5) a **collecting stage** S_2, by means of which a disturbing voltage can be added to the output voltage of the process analogue;
6) a **square-wave generator** G for generating a square-wave voltage serving as input signal for adjusting the process analogue, or as a disturbance;
7) a **cathode-ray oscilloscope** *Osc* for displaying the voltages at various points of the circuit;
8) an *R-C* **generator** (not drawn) supplying a sinusoidal voltage with variable frequency for recording frequency-response curves and Nyquist diagrams;
9) a performance **meter** (not drawn) for measuring the accuracy of the control.

There are to be added:

10) the **supply units** supplying the necessary voltages for feeding the numerous valves in the above-mentioned parts.

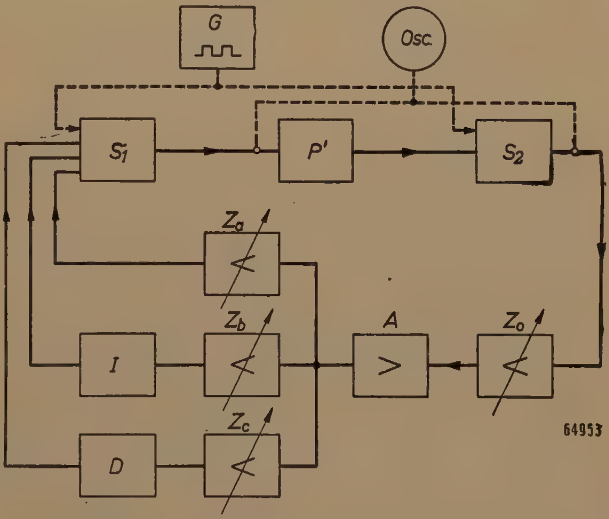

Fig. 1. Simplified block diagram of the electro-analogue. P' process analogue, with input collecting stage S_1 and output collecting stage S_2. Z_0 common attenuator, A common amplifier, I integrator, D differentiator, Z_a, Z_b and Z_c attenuators for separately adjusting the proportional, integrating and differentiating actions. The parts Z_0, A, Z_a, Z_b, I, Z_c and D form the model of a **continuously** acting controller. The square-wave generator G and the oscilloscope *Osc* can be connected at any points.

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[1]) J. M. L. Janssen and L. Ensing, The electro-analogue, an apparatus for studying regulating systems, I. Components and functions, Philips Techn. Rev. 12, p. 257-271, 1951 (No. 9), hereinafter referred to as article I.

In so far as they are of importance, and as far as space permits, details of these parts will be discussed below, but first there are some general questions to be considered.

Electrical "calculating networks" with which mathematical operations like adding, differentiating, integrating, etc. can be carried out, have already been rather extensively described in the literature [2]). For the details we may refer to this literature, but nevertheless a discussion of the essence of the various circuits is not superfluous here.

In the construction of the electro-analogue — an instrument for our own use — the aim has been rather to save time in its development than to economize on material. The number of valves, for instance, — about 350 in all, of which more than half are used in supply units! — could well have been reduced, but the drawback of this large number weighed less than the advantage of the greater chance that the solutions chosen would lead quickly to the object in view.

The next question has greatly influenced the general "plan" of the electro-analogue. This has been so arranged that the input and output terminals of all parts are accessible, so that with the aid of separate leads any desired combination can be obtained. For this purpose the terminals that are to be interconnected must have the same D.C. voltage level, e.g. earth potential. The method of attaining this — with separating capacitors and leak resistors — cannot be considered here on account of the large time constants that would then be needed and which would require impracticably large capacitances.

There would be so many of these R-C couplings in the closed control circuit that at a low frequency this circuit would tend to oscillate if the time constants were not chosen carefully. With decreasing frequency each R-C coupling gives a greater attenuation and at the same time a phase shift, which ultimately approaches 90 degrees. Oscillation sets in when there is a frequency for which the total phase shift of all R-C couplings together is 180° and at the same time the gain of the closed circuit exceeds unity. This state of affairs could be avoided by providing for a sufficient attenuation in one of the couplings to take place at the frequency at which the other couplings begin to contribute appreciably towards the phase shift. Then one R-C coupling would have to have a much smaller (but still considerable) time constant than all the others, for which the time constant would have to be very large. Even when the resistances of these couplings are chosen as high as possible, the required capacitances would still have to be impracticably large.

Moreover, the image on the oscilloscope, which after a switching operation becomes displaced (sometimes even disappearing entirely from the screen), would return to its original position only very slowly indeed.

In order to avoid these difficulties, in the parts listed under (1) to (5) the use of blocking capacitors has been completely avoided. In other words, the circuits have been so arranged that in addition to alternating voltages they can also transmit direct voltages.

Many of the parts referred to contain several amplifying valves. Special measures are necessary to preserve the direct-voltage adjustment of these valves and the uniformity in voltage level of the terminals that are to be interconnected. This will be referred to later.

The "special" process analogues

As mentioned in article I, the electro-analogue has three networks which can serve as process analogues, viz. a universal process analogue with which any step-function response can be obtained, and two "special" networks (R-C circuits) with which a limited number of step-function responses can be obtained. Contrary to the case with the universal process analogue, the working of the special process analogues imitates more or less the physical action of the (actual or hypothetical) processes which these analogues represent.

One of the special process analogues consists of twenty R-C sections connected direct in cascade, while the other consists of 40 R-C sections with intermediate valves preventing the feedback of one stage on the preceding sections. All sections have the same R and C values. The calculated step-function responses of the last-mentioned network for some values of the number n of sections used are given in *fig. 2*.

The two networks are combined electrically and mechanically into one unit. *Fig. 3* represents the circuit. The valves are connected as cathode-followers. This has the advantage that the output impedance is low (about 1000 ohms), so that other parts of the electro-analogue having an input impedance of the order of 1 megohm can be connected to the output without thereby appreciably changing the output voltage. The gain per stage is somewhat less than 1 (about 0.94), but this is no objection here

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[2]) See, e.g., F. C. Williams, F. J. U. Ritson and T. Kilburn, Automatic strobes and recurring selectors, J. Inst. El. Engrs 93 IIIA, 1275-1300, 1946, and B. Chance and others, Waveforms (Massachusetts Institute of Technology, Radiation Laboratory Series No. 19), New York 1949.

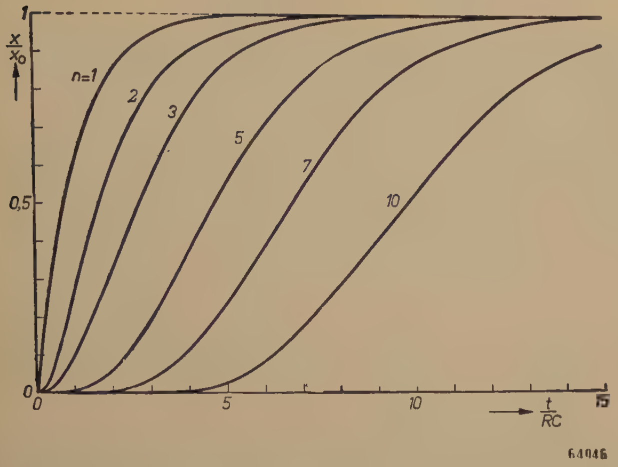

Fig. 2. Step-function response of an *R-C* network consisting of *n* sections with amplifying valves connected between the sections, for different values of *n*.

because the total voltage drop in the process analogue is compensated in the collecting stage.

As mentioned in the introduction, no grid capacitors are used. Consequently the supply has to come from two voltage sources, one supplying about + 200 V and the other —200 V with respect to earth. Each of the cathode resistors ($R_1 + R_2$) has a tapping to which an output terminal is connected and also the resistor *R* of the following section. The cathode resistors have been so dimensioned that the tappings are at approximately earth potential, while the necessary positive voltage is applied to the cathodes. The potential of the output terminal that is to be used is previously made exactly zero by adjusting the positive supply voltage, which for this purpose can be varied between 160 and 240 V.

Fig. 4 shows the construction in the form of a shelf which can be slid into one of the panels of the electro-analogue. The 40 triode systems are contained in twenty ECC 40 valves, ten of which can be seen on the photograph. On the left is the front of the shelf fully occupied with plug sockets for bringing into action the desired number of sections of the kind required (with or without intermediate valves).

Of course the number of special networks need not be restricted to these two. If necessary the shelf illustrated here can be replaced by one containing some other network required to serve as process analogue.

The "universal" process analogue

For the principle of the universal process analogue reference is made to figures 6, 7, 8 and 9 of article I. The main components are: (1) the delay network, (2) the converting network, and (3) the system with which fractions of voltages derived from the parts sub (1) and (2) can be adjusted and added together. These parts will now be discussed in succession.

The delay network

The delay network consists of 50 sections connected in cascade and built up from inductors and capacitors. These sections have to be so arranged that a voltage step (or any other voltage variation) at the input is transmitted unattenuated and undistorted but with a certain delay τ per section. This means, in the first place, that the network has

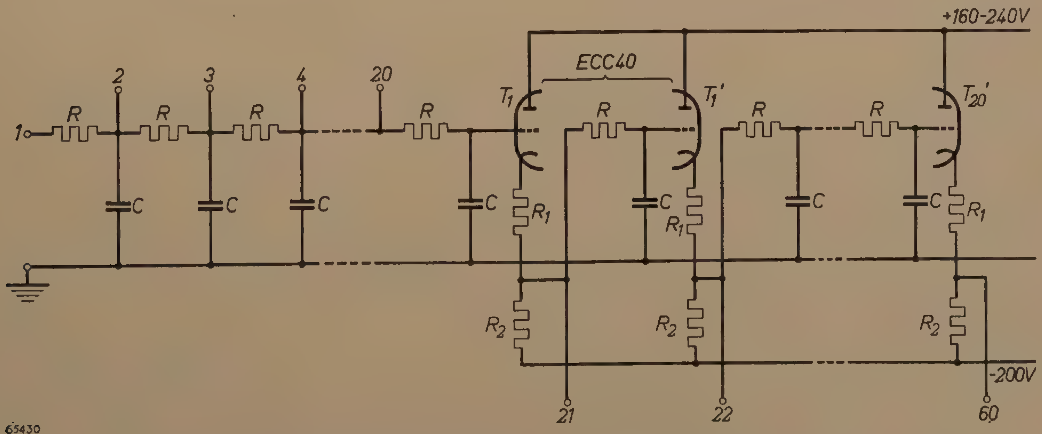

Fig. 3. Twenty *R-C* sections directly connected in cascade and followed by 40 *R-C* sections "decoupled" by valves. The valves (double triodes, ECC 40) are connected as cathode followers. The first, T_1, acts as output valve of the network with direct cascade connection, of which terminal *21* is thus always the output terminal. If, for instance, it is desired to use 5 sections of this network, terminal *16* is chosen as input terminal. For the network with interposed valves terminal *20* is always the input terminal; as output terminal one of the terminals *21* . . . *60* is chosen according to the number of sections required.

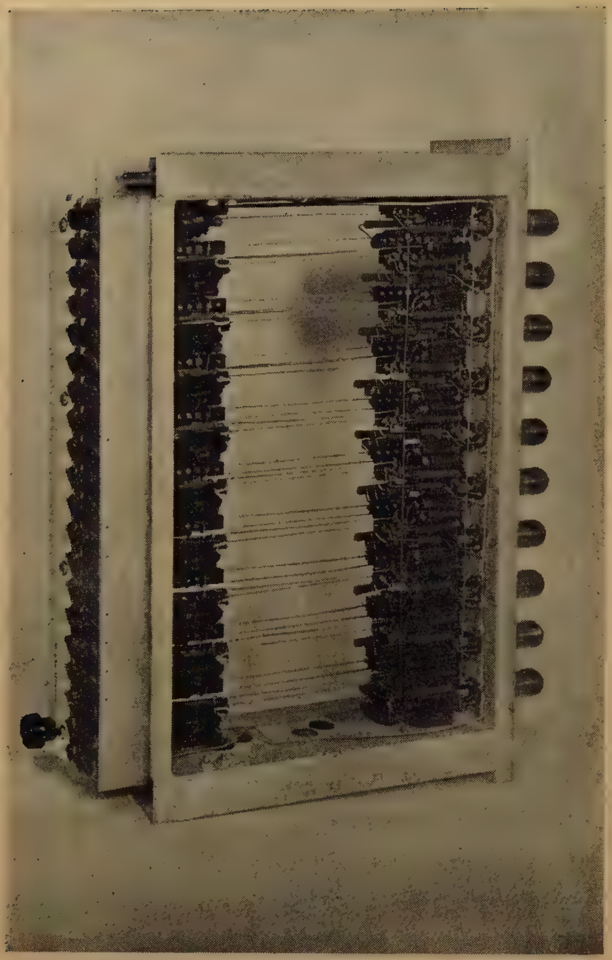

Fig. 4. Shelf containing the two special process analogues according to fig. 3. On the left the plug sockets (*1 ... 60* in fig. 3), on the right ten of the twenty ECC 40 valves can be seen.

to be terminated with its characteristic impedance, so that no reflections occur, and further that each section has to pass on a sinusoidal voltage with a phase shift β proportional to the frequency ($\tau = \beta/\omega$, where ω is the angular frequency).

The circuit of one section is given in *fig. 5a*. It is equivalent to the circuit in fig. 5*b* if $2C_1 = C'$, $L = L' + M'$, $\frac{1}{2}M = M'$ and $\frac{1}{2}C_2 = C''$. The latter circuit has been so drawn that it can be split into two symmetrical parts, one of which is represented in fig. 5*c*. We shall now consider what conditions the quantities have to fulfil in order to give the network the desired properties as near as possible.

The transmission of a section, i.e. the ratio of the output voltage V_2 to the input voltage V_1 (fig. 5*a*), regarding both as complex quantities, can be written as:

$$\frac{V_2}{V_1} = \mathrm{e}^{-\Theta} = \mathrm{e}^{-(\alpha+\mathrm{j}\beta)}, \quad . \; . \; . \; . \quad (1)$$

where the real part α of the complex quantity Θ is a measure of the attenuation taking place in that section. The parameters of the network have to be so chosen that α is zero for all frequencies and β is proportional to ω.

The first condition can be fulfilled exactly (at least in so far as the losses and undesired capacitances of the circuit elements can be ignored by ensuring that

$$\frac{C'}{4C''} = \frac{L' + M'}{L' - M'}, \quad . \; . \; . \; . \; . \; . \quad (2)$$

for which we write m^2.

This formula follows from the condition that the characteristic impedance of the network must be real for all frequencies, which means to say that the product of the no-load and short-circuit impedances of the half section (fig. 5*c*) must have a positive value for all frequencies.

For the further working out of this and the following formulae the reader is referred to the literature on the subject [3].

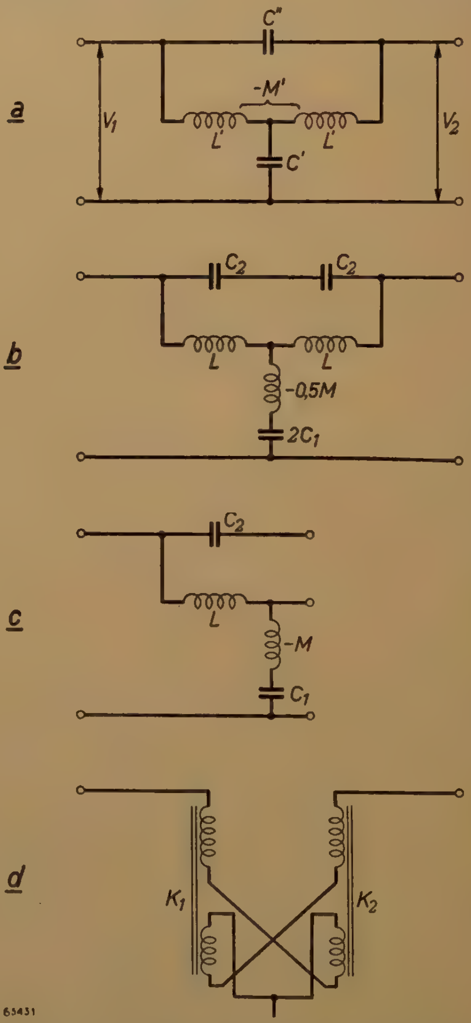

Fig. 5. *a*) Section of the delay network. *b*) Equivalent circuit of (*a*). *c*) Half of the symmetrical circuit (*b*). *d*) Execution of the two coils with self-inductance L' and mutual inductance M'. K_1 and K_2 are separate cores as used in loading coils.

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[3] M. H. Hebb, C. W. Horton and F. B. Jones, On the design of networks for constant time delay, J. appl. Phys. **20**, 616-620, 1949 (No. 6).

The second condition can only approximately be fulfilled. In the angular-frequency range extending from zero to $\omega_0 = 1/\sqrt{LC_2}$ the approximation is as near as possible at a value of m amounting to about 1.6 (see *fig. 6*): in this range τ does not then deviate more than a few per cent from the value τ_0 applying for $\omega = 0$.

In a square-wave voltage all multiples of the fundamental frequency are represented. When such a voltage is applied to the input of the properly terminated delay network which answers the condition (2), with $m = 1.6$, and if $\omega_0/2\pi$ is much greater than the fundamental frequency of the applied voltage, then the fundamental frequency and its multiples up to $\omega_0/2\pi$ are transmitted with a practically equal delay $\tau \approx \tau_0$ per section, whilst the higher harmonics are transmitted with less delay (fig. 6). Hence the voltage at the output of, say, the tenth section (if the network is properly terminated there) appears as in *fig. 7a*: after $t = 10\tau$ there is in fact a fairly good reproduction of the applied voltage step, but prior to $t = 10\tau$ there is an oscillation with gradually diminishing frequency and increasing amplitude [4]). In this case $\tau = 56.3$ µsec, $\omega_0/2\pi = 9120$ c/s and the fundamental frequency of the square-wave voltage is 50 c/s.

If, on the other hand, the applied voltage is more or less trapezoidal, with flanks covering a time about as long as the delay τ of the network, then the harmonics with frequencies higher than $\omega_0/2\pi$ are so weak that the oscillation is invisible (fig. 7*b*). This is one of the reasons why the square-wave voltage is in fact converted into a practically trapezoidal voltage. The other reason is that the output voltage of the process analogue then has the shape of a series of straight sections much more closely resembling a continuous curve than the echelon-shaped curve which would be obtained with a square-wave input voltage (cf. article I, figs 7 and 9). Owing to various causes the curve actually obtained is in fact continuous.

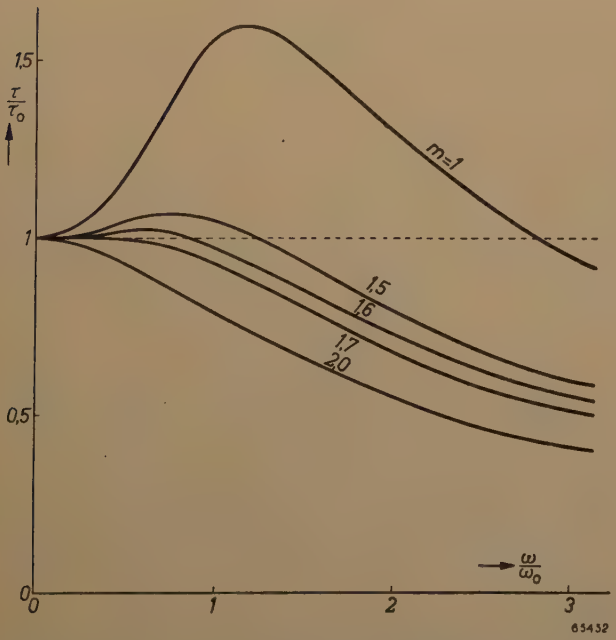

Fig. 6. The delay time τ per section according to fig. 5 (when eq. (2) is fulfilled) as a function of the angular frequency ω for different values of the parameter m. (For the meaning of τ_0, ω_0 and m see the text.) For $m \approx 1.6$, τ is practically constant in the range $0 \leqq \omega \leqq \omega_0$.

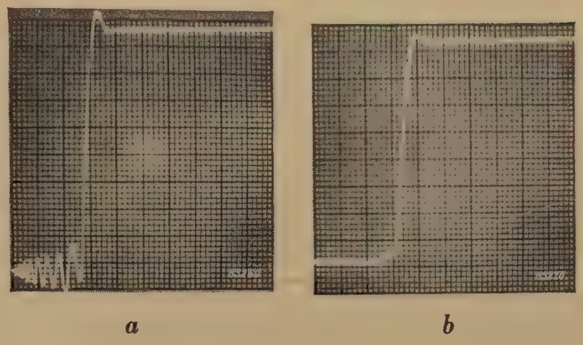

Fig. 7. Oscillograms of the voltage at the output of the tenth section of the delay network when this is terminated immediately behind that section. In (*a*) at the input of the network a voltage step was applied, and in (*b*) a voltage gradually rising from zero to maximum in about the time τ and then remaining constant. (Owing to the constricted time scale it is not very clearly shown that in (*b*) the steepest part of the curve is much less steep than in (*a*).)

The converting network

The square-wave generator voltage is converted into a trapezoidal voltage in a network (*0*, *fig. 8*) for which ten identical *R*-*C* sections with intermediate valves have been chosen. Thus voltages are obtained having the shape as represented in fig. 2. The voltage for $n = 10$ is suitable for our purpose provided the time constant *RC* is suitably chosen, such that the "dead time" between the voltage step at the input and the appearance of the output voltage is practically equal to the delay time τ of the filter. If it is desired to imitate a process which on the time scale of the analogue has a shorter "dead time", or none at all, then this can be done by including in the output voltage of the process analogue also other voltages from intermediate sections of the converting network, say from the first, the third and the sixth sections (see fig. 8).

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[4]) The question arises why, instead of a network uniformly transmitting voltages of all frequencies, use is not made of a low-pass filter with a cut-off frequency round about $\omega_0/2\pi$, for then the higher harmonics in question would be suppressed. The answer to this is that, with a voltage step on the input, a low-pass filter always shows a natural oscillation, which in the present case is likewise very disturbing, no matter how well the filter is terminated (see, e.g., Philips Techn. Rev. **12**, 239, 1951 (No. 8), fig. 11*b*).

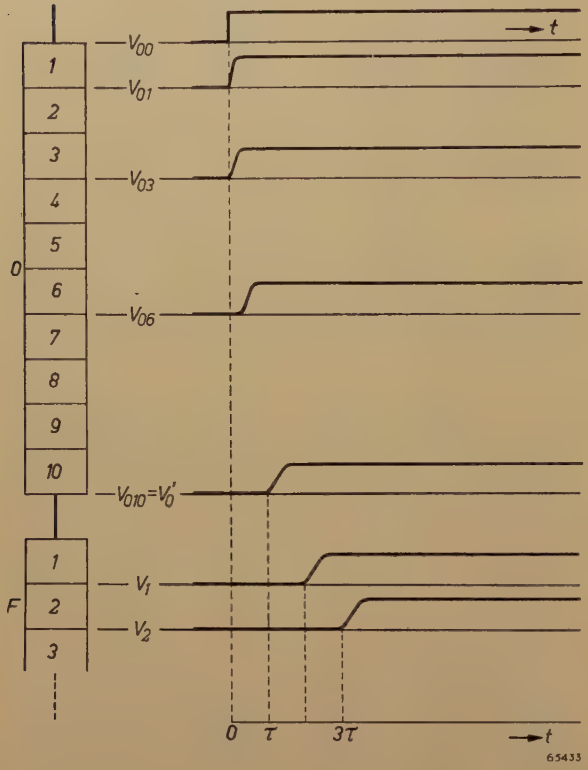

Fig. 8. Delay network F preceded by a network 0 converting the voltage step V_{00} into the gradually rising voltage V_{010} (referred to in article I as V_0').

For the details of the circuit see the right-hand half of fig. 3.

Varying and adding fractions of the output voltages of the delay and converting networks

For the process analogue to give the conditions of any arbitrary process, i.e. for adjusting any arbitrary step-function response curve, variable fractions of the voltages $V_1 \ldots V_{50}$ at the outputs of the sections of the delay network have to be added together; it may be necessary to add also fractions of the voltages V_{01}, V_{03}, V_{06} and V_{010} from the converting network. The result is a sum voltage V_s':

$$V_s' = [a_{01}\,V_{01} + a_{03}\,V_{03} + a_{06}\,V_{06} + a_{010}\,V_{010}] + [a_1\,V_1 + \dots + a_{10}V_{10}] + [a_{11}\,V_{11} + \dots + a_{20}V_{20}] + \dots + [a_{41}\,V_{41} + \dots + a_{50}\,V_{50}] \quad . \; . \; . \; . \; . \; . \; . \; (3)$$

V_s' may show the shape of any desired step-response curve, provided the coefficients a in (3) can be varied independently of each other from $-a_{\max}$ to $+a_{\max}$. This variability is obtained by amplifying each of the 54 voltages $V_{01} \ldots V_{50}$ in a push-pull stage as shown in *fig. 9* [5]. The output voltage V_0 appears at the sliding contact of a potentiometer R_4 between the anodes and by means of this contact can be varied from $-\frac{1}{2}\,\mu$ to $+\frac{1}{2}\,\mu$ times the input voltage V_i; here μ represents the total gain of the stage.

For adding up the output voltages the 54 push-pull amplifiers are divided into six groups, denoted in (3) by square brackets. The first group has four amplifiers, while the other five groups, connected to the sections of the delay network, each have ten.

Adding is done in two steps: first the four, or ten, output voltages from the push-pull amplifiers belonging to one group are added together in a "sub-collecting stage", after which the six group voltages obtained in this way are added together, this taking place in the output collecting stage of the process analogue (S_2 in fig. 1).

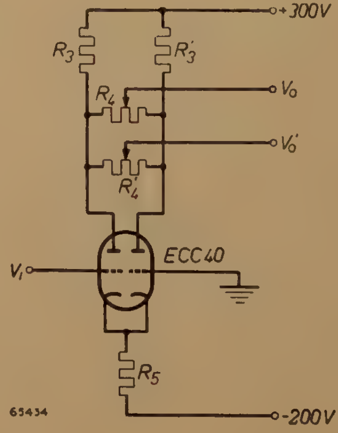

Fig. 9. Push-pull circuit for amplifying the output voltages of the converting network and of the delay network. R_3, R_3' anode resistors of the double triode ECC 40. The high cathode resistance R_5 ensures symmetry in spite of the asymmetrical input. With the potentiometer R_4 the respective coefficient a of eq. (3) can be varied from $-a_{\max}$ to $+a_{\max}$. In each push-pull amplifier there is a second potentiometer (R_4'), independent of the first, for adjusting a second step-response curve.

Fig. 10 shows the circuit of one of the sub-collecting stages [6]. By means of equal resistors R_6 the output terminals of the push-pull amplifiers of one group are connected to one collecting point (in this case G_2). The voltage obtained at this point is the average of the voltages at the output terminals and thus, except for a constant factor (4 or 10),

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[5] The working of this push-pull circuit, which has an asymmetrical input, is explained, i.a., in an article by E. E. Carpentier in Philips Techn. Rev. **9**, 204, 1947, fig. 3*b*.

[6] Similar (and other) adding networks are described in the book (pages 629-648) quoted in footnote [2].

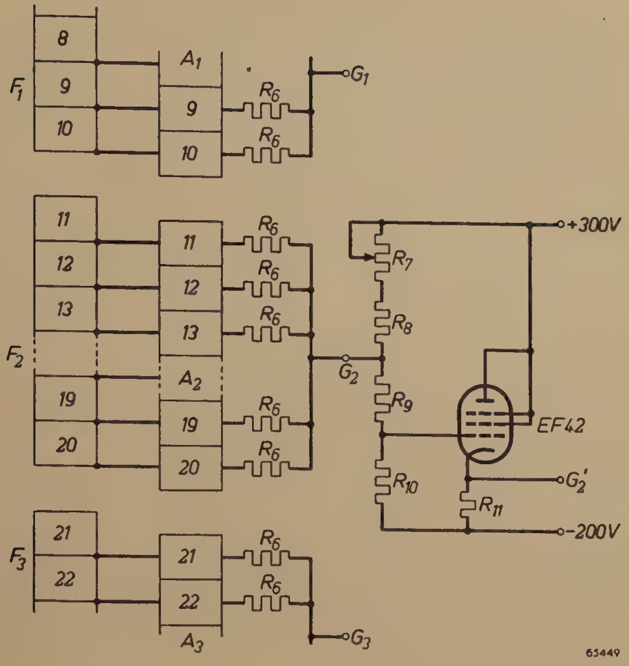

Fig. 10. Sub-collecting stage, in which the ten output voltages of a part (F_2) of the delay network are added together after amplification by the push-pull amplifiers A_2 (fig. 9). (F_1 the preceding, F_3 the following ten sections, with corresponding amplifiers A_1 and A_3.) The outputs of the amplifiers are connected via resistors R_6 to collecting points G_1, G_2, G_3, etc. The EF 42 valve, used as a cathode follower, and the resistors R_7 ... R_{11} provide for a low-impedance output with a zero direct-voltage level.

is equal to the desired sum. Via a cathode follower (this is necessary owing to the low output impedance needed) the voltage is transmitted from G_2 to the group output terminal G_2'. By means of a potentiometer formed by the resistors $R_7 \dots R_{10}$, with R_7 variable, the direct voltage at G_2' is brought down to zero (that at G_2 is about + 150 V). This potentiometer is so dimensioned that in the state of rest no current flows through the ten resistors R_6 and the sliding contacts of the potentiometers R_4 (fig. 9), no matter in what position these sliding contacts may be; thus the direct-voltage level of the collecting points does not change when the coefficients a are varied.

The second step in the addition is the adding together of the six group output voltages. As already stated, this takes place in the output collecting stage of the process analogue (S_2 in fig. 1). This stage also affords an opportunity to add to the sum a sinusoidal or step "disturbance", so that it can be ascertained how the controlling circuit reacts to such a disturbance (examples of this have been given in article I). The construction of this collecting stage will be described below.

Construction of the universal process analogue

The universal process analogue is contained in six shelves, each carrying one of the groups previously mentioned. Such a shelf is illustrated in *fig. 11*. In the middle there are 20 coils, pairs of which belong to each section of the delay network (fig. 5*a*). The necessary mutual inductance M' is obtained by arranging the coils as represented in fig. 5*d*. At the top on the right-hand side of the shelf shown in fig. 11 is the valve EF 42 of the sub-collecting stage (cf. fig. 10), and underneath that are the ten double triodes ECC 40 of the push-pull amplifiers (fig. 9). As indicated in the last-mentioned illustration, in addition to the potentiometer R_4 there is another, R_4'; accordingly also the sub-collecting stage is duplicated. The reason for this is that by this means two different step-responses can be obtained, either for two values of one of the working quantities (in the case of temperature control, for instance, for two ambient temperatures), or for two detecting elements at different points in the process (one serving for the control and the other as a means of observing the behaviour of the controlled quantity elsewhere in the process). On the left-hand side of the shelf in fig. 11 are the 20 knobs of the potentiometers R_4 and R_4'.

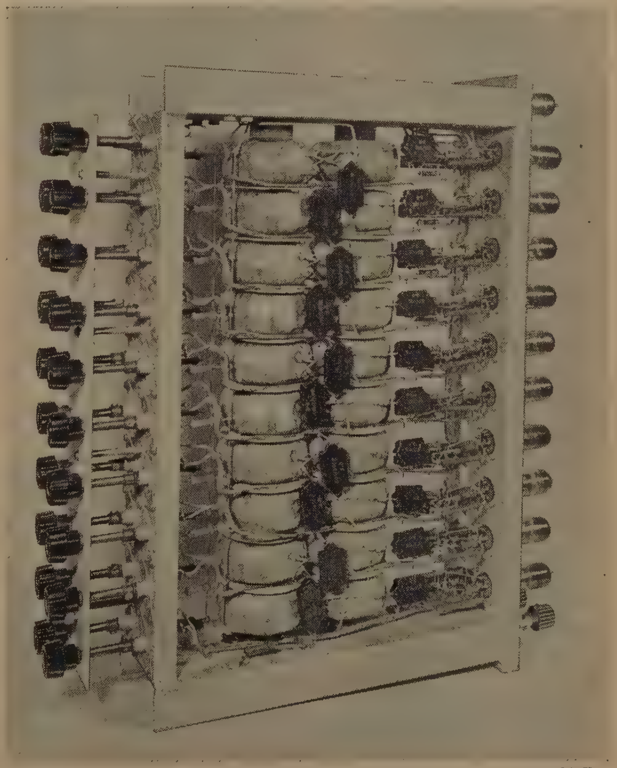

Fig. 11. Shelf with ten sections of the delay network. On the left the knobs of the 20 potentiometers R_4 and R_4' (fig. 9), in the middle the coils and capacitors (fig. 5), and on the right the amplifying valves.

Fig. 12 shows the front of the electro-analogue. In the panel on the right are five of the shelves (F) described. Underneath these is a shelf Q containing the two special process analogues previously described. If it is desired to work with the universal process analogue the bottom shelf has to be replaced by another containing the converting network with accessories.

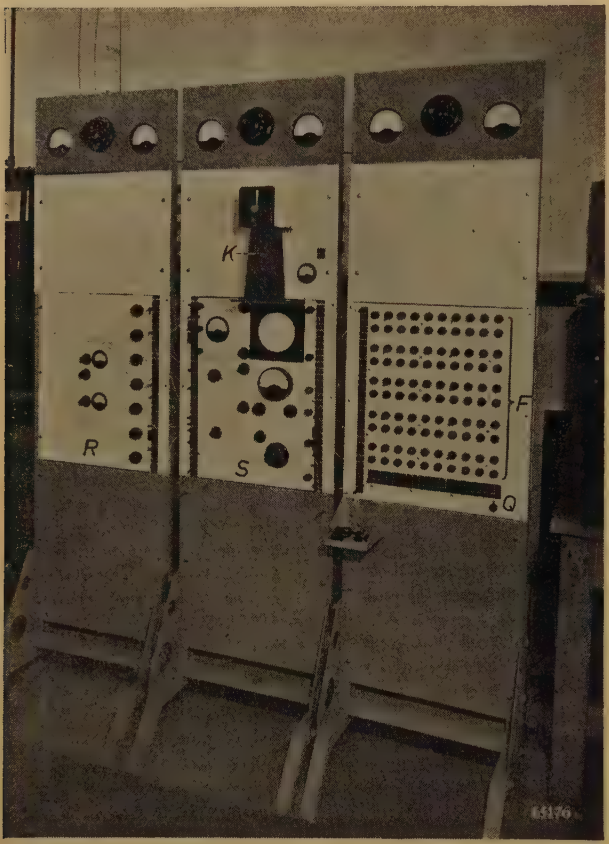

Fig. 12. Front of the electro-analogue. R panel with controller models, S panel with oscilloscope, collecting stages, square-wave generator and R-C generator, F delay network, Q special process analogues. When the universal process analogue is used Q is replaced by a shelf with the converting network (O in fig. 8). K cylinder which can be turned down for photographing the oscillograms.

The "universal" amplifier

Amplifiers are used at several points in the controlling circuit of the electro-analogue, not only at the point marked A in the block diagram (fig. 1) but also in the collecting stages (S_1 and S_2), in the integrator (I), in the differentiator (D) and in the oscilloscope (Osc). Apart from small modifications, most of these amplifiers are built according to the same principle, and that is why we speak here of an "universal" amplifier.

Briefly, the universal amplifier consists of three push-pull stages in cascade, the first with an asymmetrical input and the last one connected as a cathode follower in order to get a low output impedance. As already said, there are no grid capacitors, because these would lead to phase shifts and thus cause the controlling circuit to oscillate. By applying negative feedback a high degree of stability is obtained.

For a D.C. voltage amplifier a push-pull circuit offers several advantages. When a pair of valves connected in push-pull have a common cathode resistor and a common screen-grid resistor, provided there is absolute symmetry, the currents through these resistors are constant, regardless of the input voltage, and thus also the cathode voltage and the screen-grid voltage are constant. These resistors, therefore, do not involve any reduction of the gain (as they would do in an asymmetrical amplifier unless they are shunted by large capacitors, a remedy which of course is ineffective for a direct voltage). In the second place, any differences arising between a pair of valves only slightly disturbs the symmetry: the common resistors aim, as it were, at preserving the symmetry (see footnote [5])). Finally, in the electro-analogue it is convenient to have a symmetrical output voltage even if only one of the two voltages (with respect to earth) is used: for the control one can take the voltage that has the right sign; without such a possibility it would in some cases be necessary to have an "inverter stage" for reversing the sign of the voltage.

The measures described are applied in the somewhat simplified circuit of the universal amplifier (*fig. 13*), which is explained in the subscript.

In order to avoid any disproportionality in, for instance, the push-pull amplifiers (fig. 9) behind the delay network, once the D.C. voltage levels have been adjusted they must not be liable to any change. It is therefore necessary that the supply voltages for the amplifier are absolutely constant. The anode and grid voltages are obtained from carefully stabilised rectifiers (+600 V, +300 V and —300 V). A fourth stabilised rectifier supplies the filament current for the six pentodes in the amplifier: in the case of A.C. supply from the mains the mains fluctuations would cause too great asymmetries — in spite of the aforementioned "aim at symmetry" — owing to the two valves in a push-pull stage never being exactly identical. Since D.C. supply is used, valves of the U type have been chosen (UF 41) with a filament current of only 100 mA at 12.6 V. Eighteen filaments connected in series are fed from one rectifier.

The over-all gain (the ratio of the output voltage, with respect to earth, to the input voltage) is 200 (46 dB).

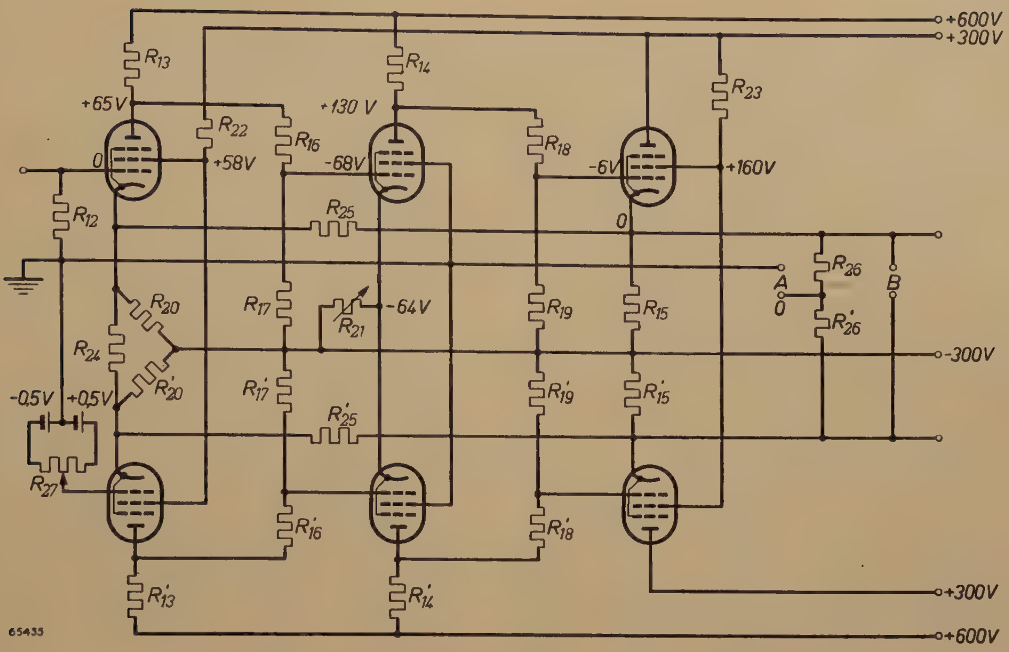

Fig. 13. Circuit diagram of the universal amplifier (simplified). R_{12} input resistor, R_{13}, R_{13}' anode resistors of the first stage, R_{14}, R_{14}' ditto of the second stage, R_{15}, R_{15}' cathode resistors of the third stage (cathode-follower circuit). R_{16}-R_{17}, R_{16}'-R_{17}', R_{18}-R_{19}, R_{18}'-R_{19}' form voltage dividers by means of which the control grids of the next stage are brought to the right potential. R_{20}-R_{20}' (to be imagined, to a first approximation, as being connected in parallel, since R_{24} has a much smaller resistance) is the common cathode resistor of the firsts tage, R_{21} is that of the second stage. R_{22} and R_{23} are the common screen-grid resistors of the first and third stages respectively. R_{24} is a resistor for the negative feed-back from the output terminals via the equal resistors R_{25} and R_{25}'.

For checking the direct-voltage level and the symmetry the input is short-circuited and a moving-coil voltmeter is connected in succession to A and to B. At A the mean value of the voltage at the output terminals ($R_{26} = R_{26}'$) is measured with respect to earth; this voltage is reduced to zero by adjusting R_{21}, which affects in equal sense the cathode currents and thus also the anode currents and anode voltages of the second stage. At B the potential difference between the two output terminals is measured, and thus the degree of asymmetry; this difference is brought to zero with the aid of the potentiometer R_{27}, with which the control-grid voltage of one of the valves in the first stage can be varied from about -0.5 V to $+0.5$ V (actually R_{27} is not fed from a battery but from the $+300$ V and -300 V sources).

The correct D.C. voltages (with respect to earth) of the various points are indicated in the diagram.

The six valves are of the UF 41 type.

The collecting stages

The purpose of the collecting stage S_1 (fig. 1) is to form the sum of the output voltages from the parts comprising the continuously acting controller, to which sum it should be possible to add a disturbing voltage. In the collecting stage S_2 — when the universal process analogue is used — it is the output voltages from the sub-collecting stages that have to be added together, possibly also with a disturbing voltage. Furthermore, the collecting stages together have to provide for a gain which at least compensates the attenuation taking place in the process analogue. As mentioned in the discussion of the oscillograms in article I, what is desired is that a step voltage with amplitude s applied to the input of the process analogue (after this has temporarily been disconnected from the controller) should produce at S_2 an output voltage with final value x_∞ exactly equal to s, because then it is easiest to interpret the oscillograms. Now the fact that the collecting stages also have to function as amplifiers makes it impossible for them to have the same circuit as the sub-collecting stages (fig. 10), for the "gain" of the latter is less than unity. Use is therefore made of a "universal" amplifier (fig. 13), but with a small modification related to the following question.

In the sub-collecting stages the adding together of n voltages ($V_1 \dots V_n$) is done with the aid of n equal resistors (R_6, fig. 10) coming together at one collecting point. This point assumes a potential equal to the mean value of the n voltages $(V_1 + \dots + V_n)/n$. If n is constant, as it is in the case of the sub-collecting stages (namely either always 10 or always 4), then this mean value differs from the desired sum, $V_1 + \ldots + V_n$, only by a constant factor $1/n$. In the case of the collecting stages that we are now about to consider, however, n is variable: for S_1 it varies from $n = 1$ (in the case of a controller with, for instance, only a proportional term) to $n = 6$ (controller with a proportional, a single and a double integrating, and a single and a double differentiating term, plus a disturbance voltage), for S_2 from $n = 1$ (when one of the special process analogues is employed) to $n = 7$ (six sub-collecting stages of the universal process analogue plus a disturbance voltage). The effect of a variation of n could be compensated with a corresponding but opposite variation of the gain, but a simpler method is that described below whereby the sum of the voltages is obtained with a proportionality factor practically independent of n.

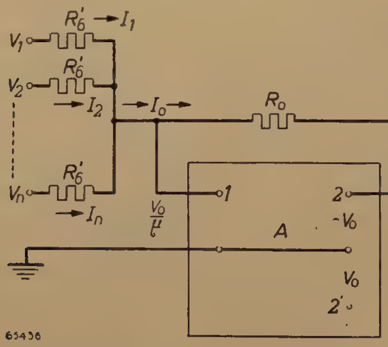

Fig. 14. Circuit diagram of a collecting stage. V_1 ... V_n are the voltages (variable in number) that are to be added together. A universal amplifier according to fig. 13. When the gain μ is high the output voltage is approximately equal to the product of the sum $(V_1 + \ldots + V_n)$ and the ratio of the resistances R_0 and R_6'.

In *fig. 14* the amplifier A has an asymmetrical input and a symmetrical output, as, for example, the universal amplifier previously discussed. The input terminal *1* is connected via equal resistors R_6' to the n points from which the voltages $V_1 \ldots V_n$ have to be added together, and, moreover, via a resistor R_0 to the output terminal *2* where the voltage is in counter-phase to that at terminal *1*. The output voltage (with respect to earth) is denoted by V_o. If the gain μ is very high, then to a first approximation the voltage V_o/μ at terminal *1* is negligible compared with the input voltages $V_1 \ldots V_n$, so that for the currents $I_1 \ldots I_n$ flowing through the resistors R_6' we then have:

$$I_1 \approx \frac{V_1}{R_6'}, \ldots, I_n \approx \frac{V_n}{R_6'} \quad . \quad . \quad . \quad (4)$$

If V_o/μ is also negligible with respect to V_o then the current I_0 flowing through R_0 is:

$$I_0 \approx \frac{V_o}{R_0} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

From:

$$I_0 = I_1 + I_2 + \ldots + I_n$$

it follows, by applying the equations (4) and (5), that

$$V_o \approx \frac{R_0}{R_6'}(V_1 + \ldots + V_n).$$

From this formula it is seen that — provided the gain μ is high enough — the output voltage is equal to a fixed ratio (independent of n) multiplied by the sum of $V_1 + \ldots + V_n$.

From an exact calculation, however, we find:

$$V_o\left(1 + \frac{1}{\mu} + \frac{nR_0}{\mu R_6'}\right) = \frac{R_0}{R_6'}(V_1 + \ldots + V_n),$$

in which the quantity n still occurs. With the values used for R_0 (about 5 megohms) and R_6' (1 megohm) and with the normal gain of the universal amplifier (μ = 200) the coefficient of V_o is equal to 1.03 for $n = 1$ and 1.18 for $n = 7$, so that there is still rather a great dependency upon n. For this reason, in the amplifiers employed in the collecting stages the resistor R_{24} (fig. 13) for the negative feedback is short-circuited, so that μ is about 1500 and the coefficient of V_o varies only from 1.004 to 1.024.

There is no objection against the negative feedback being cut out by shorting R_{24}, since the resistor R_0 introduces a new and much heavier feedback. By making R_0 variable (from 0.85 to 5.4 megohms) the gain of the collecting stage can be varied within certain limits (in the present case from 0.85 to 5.4).

The integrator and the differentiator

As far as the circuit is concerned, the integrator and the differentiator are only modified forms of the collecting stage. When, in the diagram of the latter (fig. 14), we take only one of the n input resistors (now to be called R) and replace R_0 by a capacitor C, then, as will be seen from what follows, we have an integrator (*fig. 15*), and when interchanging R and C we have a differentiator.

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7) For differentiating and integrating networks see, e.g., pages 648-666 of the book quoted in footnote 2).
On account of the capacitor C between output and input, an integrator according to the system of fig. 15 is known under the name of a Miller integrator, named after the first scientist to study the influence of capacitance between anode and grid of a triode, though he did not then have an integrating effect in mind (J. M. Miller, Sci. Papers Nat. Bur. Stand. No. 351, 15, 367-385, 1919-1920).

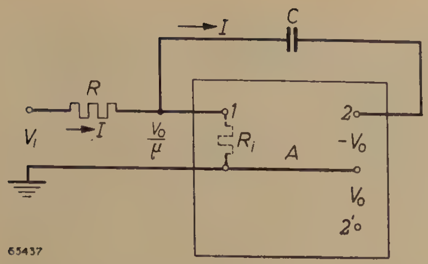

Fig. 15. Basic circuit of the integrator. *A* is a universal amplifier according to fig. 13.

The integrator

If the universal amplifier *A* again has a very high gain μ, then to a first approximation the voltage V_o/μ at the input of *A* is negligible compared with the input voltage V_i. The current *I* flowing through *R* and *C* is then:

$$I = \frac{V_i}{R} = C\frac{\mathrm{d}V_o}{\mathrm{d}t}, \quad . \; . \; . \; . \; . \; . \quad (6)$$

or

$$V_o = \frac{1}{RC}\int V_i\,\mathrm{d}t\,,$$

so that — at least when ignoring V_o/μ — the output voltage is proportional to the time integral of the input voltage.

To find the frequency characteristic of the integrator we let V_i change sinusoidally with time, with angular frequency ω. Equation (6) then becomes

$$I = \frac{V_i}{R} = V_o \cdot \mathrm{j}\omega C\,,$$

or

$$\mu' = \left|\frac{V_o}{V_i}\right| = \frac{1}{\omega CR}.$$

Thus the characteristic varies in inverse proportion to the frequency (curve *1* in *fig. 16a*). The finite value of μ, however, prevents an unlimited increase of the quantity μ' with decreasing frequency; the actual frequency characteristic is therefore a curve like *1'* and does not exceed the value μ.

If account is taken of the finite value of μ then account should also be taken of the finite value of the input resistance R_i (indicated by the broken line in fig. 15). This R_i is the resistor R_{12} in fig. 13. According to the valve specifications this resistance must not exceed 1 megohm, which value has been chosen for the resistor *R*.

Better expression is given to the behaviour of the integrator when the two coordinates of the frequency characteristic are on a logarithmic scale (fig. 16*b*): the hyperbola in fig. 16*a* then becomes a descending straight line *1*, corresponding to the behaviour of an ideal integrator. If the integrator is not an ideal one then with decreasing frequency this straight line ultimately changes into a horizontal line *2* lying at a level determined by the gain μ. The abscissa of the point of intersection of the two straight lines (for the sake of simplicity the curved transition is not usually drawn) indicates roughly the lowest frequency for which the integrator can still be used.

As is immediately seen from fig. 16*b*, the higher the gain μ, the lower is this limit. With the values chosen for *R* and *C* (respectively 1 megohm and 1000 pF), upon which, of course, the position of the point of intersection also depends, the value $\mu = 200$ of the universal amplifier gave a frequency limit which was not low enough for our purpose. Just as in the case of the collecting stage, the gain might be increased by short-circuiting the resistor for the negative feedback, but for the integrator

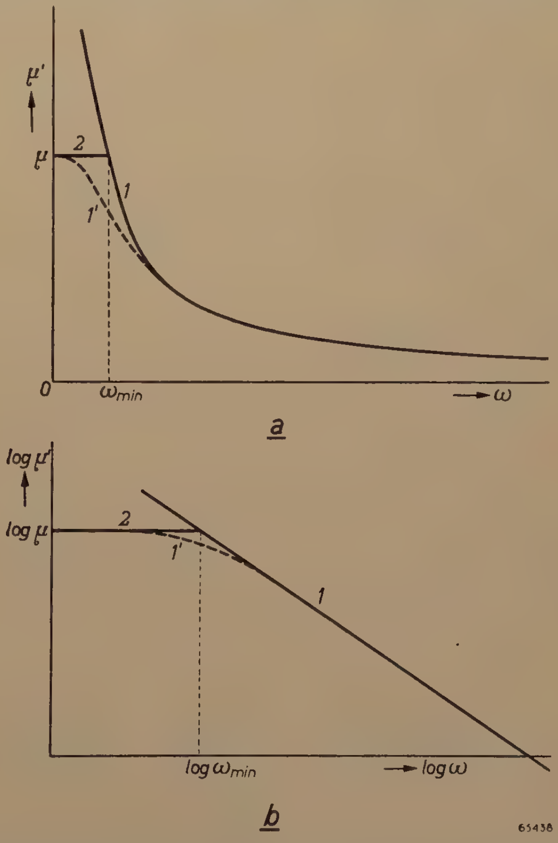

Fig. 16. *a*) Frequency characteristic of the integrator, on a linear scale. Curve *1* applies for an ideal integrator ($\mu = \infty$), curve *1'* for an integrator with finite value of μ. *b*) The same but with both coordinates on a logarithmic scale. The characteristic of the ideal integrator is the straight line *1*, which, when μ is finite, at low frequencies ultimately changes to the horizontal line *2* (see also (*a*)). The continuous transition *1'* between *1* and *2* is not usually drawn. A line dropped from the point of intersection of *1* and *2* to the abscissae indicates the lowest frequency (ω_{min}) for which the integrator can still be used.

this appeared to lead to instability. Therefore another method has been followed, which is explained in the following small-type text and which offers the theoretically interesting possibility of obtaining an ideal integrator.

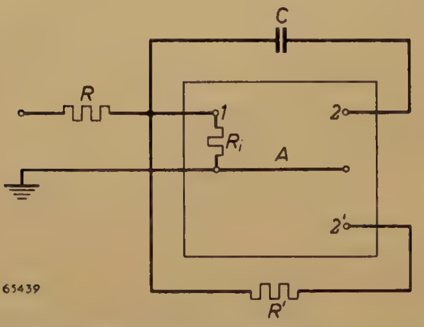

Fig. 17. The working of the integrator can be improved by adding a given resistance R' between the terminals *1* and *2'* of the system represented in fig. 15.

When the input terminal *1* of the amplifier (see *fig. 17*) is connected not only via the capacitor C to the output terminal *2* but also via resistor R' to the other output terminal *2'* (where the voltage is in phase with that at terminal *1*), a simple calculation shows that μ has to be replaced by the apparent gain μ_1:

$$\mu_1 = \frac{\mu}{1+\frac{R}{R_i}-\frac{R}{R'}(\mu-1)},$$

where R_i is the input resistance of the amplifier. This expression becomes infinitely large when R' is so chosen that

$$1+\frac{R}{R_i}-\frac{R}{R'}(\mu-1)=0,$$

or

$$R'=(\mu-1)\frac{RR_i}{R+R_i}.$$

If this condition is fulfilled an ideal integrator is obtained but it is then on the limit of direct-voltage instability. This does no harm so long as the control circuit is closed, but the presetting of the amplifier (resistors R_{21} and R_{27}, see fig. 13) has to be done with the circuit open, and then difficulties arise. For R' we have therefore chosen a somewhat larger value than is indicated by the last formula.

As a matter of fact the question whether the integrator is ideal or not is more of a theoretical than practical importance, since the integrator of the actual controller to be imitated is not ideal either. And the same applies to differentiators.

By way of an example oscillograms of the input and output voltages of the integrator are shown in *fig. 18*.

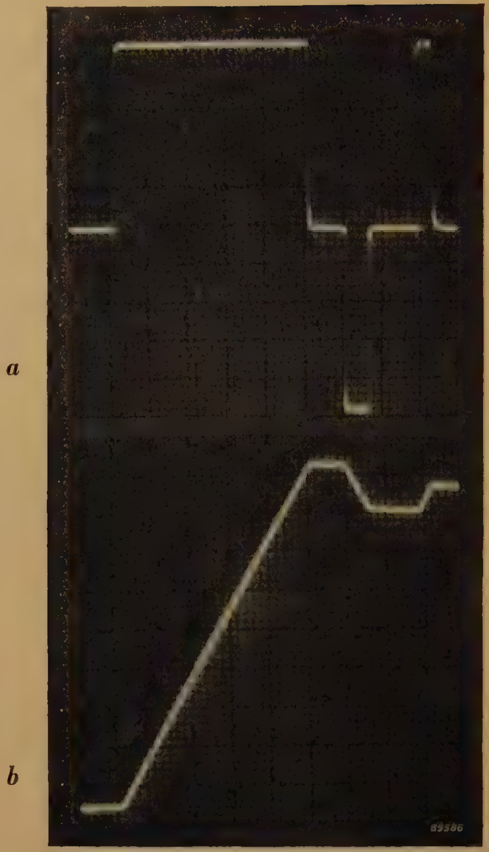

Fig. 18. To illustrate the working of the integrator a voltage of the shape of the oscillogram (*a*) is applied to the input. In (*b*), the oscillogram of the output voltage, the integral of (*a*) is easily recognized.

The input voltage (*a*) was derived from the model of the controller with three-step action, which together with the integrator forms a model of a controller with three speeds (cf. I, fig. 28).

The differentiator

When R and C in the integrator (fig. 15) are interchanged we have a differentiator (*fig. 19*). This is easily understood when again V_o/μ is considered, to a first approximation, to be negligible compared with V_i and V_o. The current I then flowing through C and R is

$$I = C\frac{dV_i}{dt} = \frac{V_o}{R}, \qquad \text{. . . . . . (7)}$$

or

$$V_o = RC\cdot\frac{dV_i}{dt}.$$

The frequency characteristic of the ideal

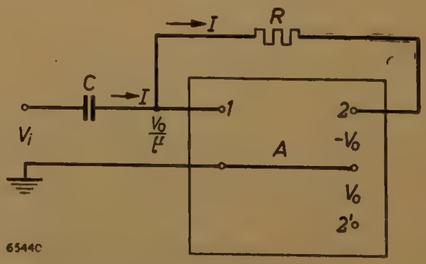

Fig. 19. By interchanging R and C in the integrator (fig. 15) a differentiator is obtained.

differentiator is found by introducing for V_i in (7) a sine function:

$$I = \mathrm{j}\omega C\, V_i = \frac{V_o}{R},$$

and hence:

$$\mu' = \left|\frac{V_o}{V_i}\right| = |\mathrm{j}\omega CR| = \omega CR.$$

Thus μ' is proportional to the frequency, and log μ' increases linearly with log ω (line *1* in *fig. 20*).

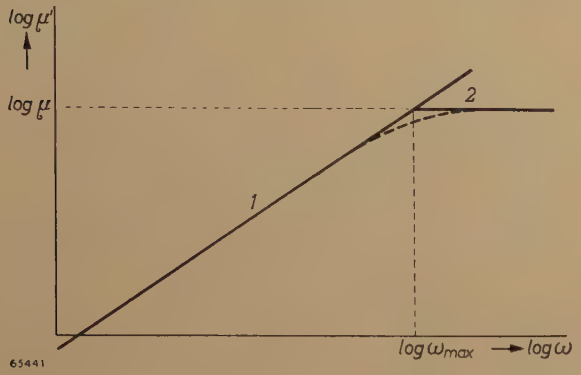

Fig. 20. Frequency characteristic of the differentiator, with both coordinates on a logarithmic scale. In analogy with fig. 16*b* the characteristic is schematically drawn to show two straight lines, *1* (characteristic of the ideal differentiator) and *2*. A line dropped from the point of intersection of *1* and *2* to the abscissae corresponds roughly to the highest frequency $\omega_{\max}$ at which the differentiator still works satisfactorily.

Owing to the finite value of μ, however, with increasing frequency log μ' ultimately runs horizontally (*2* in the same figure) at the level of log μ. Taking the point of intersection of the two straight lines as indicating the maximum frequency at which the differentiator still works satisfactorily, it is immediately seen that the larger the value of μ the higher is this limit. In the differentiators of the electro-analogue, with $C = 1000$ pF and $R = 1$ megohm, in the normal state the universal amplifier gives, with $\mu = 200$, a sufficiently high frequency limit.

For double integrations or double differentiations, two integrators or two differentiators, as the case may be, can be connected in cascade.

It is to be pointed out here that a characteristic with a proportional and a number of integrating and differentiating terms is certainly not to be regarded as *the* universal characteristic of a (continuously acting) controller; also other characteristics are possible, even when disregarding non-linear characteristics. For this reason space has been reserved in the electro-analogue for networks built up according to need to be used as a model for a continuously acting controller.

Models of discontinuously acting controllers

A circuit which can serve as model of a controller with two-step action is the flip and flop circuit, i.e. a circuit having two valves (*fig. 21*) only one of which can pass current at a time, the other thereby being cut off. When the conducting valve receives a negative voltage pulse on the grid it is cut off, the other valve then being unblocked and thus becoming conducting. When a negative voltage pulse is applied to the grid of the latter valve this in turn is cut off, and so on. Just as is the case with a controller with two-step action, there are therefore two stable conditions [8]). Moreover, a certain backlash can be obtained in the change-over so that the circuit imitates a controller with backlash (fig. 21*b* in article I), the characteristic of which is similar to a hysteresis loop.

Fig. 22 represents, in a somewhat simplified form, the circuit which in the electro-analogue functions as model of a controller with two-step action. The width of the hysteresis loop can be adjusted according to need. The working of the circuit is explained in the subscript.

Here we can only very briefly consider a controller with three-step action. The principle is illustrated in *fig. 23*. The output terminal *3* has a positive potential when only the valve *T* is conducting, earth potential so long as both valves are cut off, and a negative potential when only the valve *T'* is conducting. Thus three stable states are possible. This is the principle applied in the actual circuit, which for the rest resembles very much that of fig. 22.

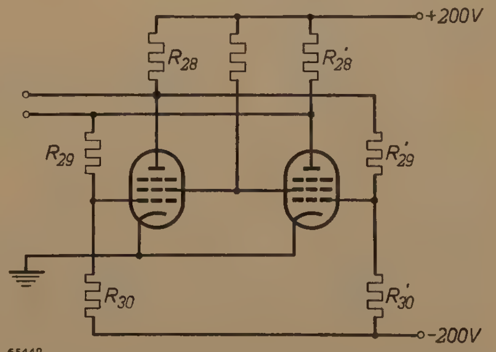

Fig. 21. Flip-and-flop circuit. Only one of the two valves is conducting at a time and thereby cuts off the other. The position is reversed when a negative voltage pulse is applied to the grid of the conducting valve. The anode resistors R_{28}, R_{28}', together with respectively the resistors R_{29}'-R_{30}' and R_{29}-R_{30}, form voltage dividers ensuring the correct adjustment.

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[8]) The same system is also applied in an entirely different field, viz. in the "scale of two" circuits of counting apparatus; see, e.g., Philips Techn. Rev. **6**, 76, 1941 and **10**, 7, 1948.

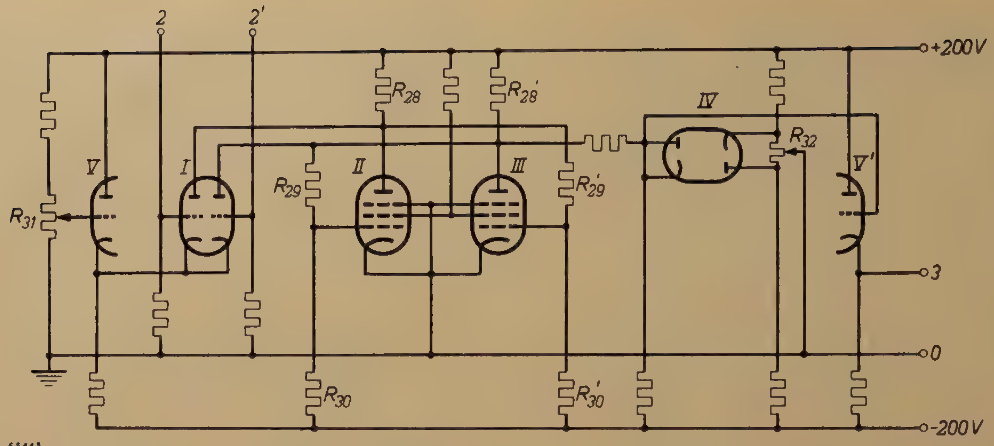

Fig. 22. Model of a controller with two-step action, in which the flip and flop circuit of fig. 21 is employed (valves *II* and *III* with the resistors $R_{28} \dots R_{30}'$). The grid-voltage pulses triggering the circuit from one stable position to the other are derived from the valve *I*, the input terminals of which, *2*, *2'*, are connected to the output of the process analogue via the universal amplifier and the output collecting stage. With the potentiometer R_{31}, via the triode *V*, it is possible to vary the cathode potential of *I* and thus the backlash of the controller; the extent of the backlash can be read from a measuring element not drawn in this diagram. The voltage fluctuations at the anode of *III* are limited by the double diode *IV* and transmitted by the triode *V'* connected as a cathode-follower. The D.C. voltage level at the output terminal *3* is reduced to zero by means of the potentiometer R_{32}.

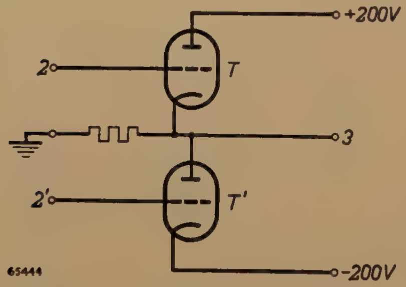

Fig. 23. Principle of a circuit corresponding to a controller with three-step action. The output terminal *3* is at a positive potential when the valve *T* is conducting, at earth potential when both valves are cut-off and at a negative potential when the valve *T'* is conducting.

When the output of this circuit is connected to an integrator one has an analogue of a controller with three speeds.

The cathode-ray oscilloscope

Vertical deflection

For the vertical deflection of the cathode-ray oscilloscope an amplifier is used which can be regarded as a greatly simplified form of the universal amplifier (fig. 13). The simplifications consist in: (1) the omission of the third stage (cathode-follower circuit), since in the present case the load of the amplifier is constant and has a high impedance, and (2) the omission of the voltage dividers between the two stages and between the second stage and the output, because in this case the D.C. voltage level at the output terminals need not be zero (it is here + 300 V, the same as that at the anode of the cathode-ray tube).

The gain is continuously adjustable by means of the resistor R_{24}, which has been made variable here (fig. 13).

Horizontal deflection

From a multivibrator synchronized with the mains voltage a voltage is obtained having the shape represented in *fig. 24* 9)**.** The amplitude of the step is 10 V and the average voltage level + 140 V. With the aid of a direct-voltage amplifier (one push-pull stage with two EF 42 pentodes) the amplitude is increased to about 100 V, with which an oscillogram can be traced across the whole width of the screen, and the direct-voltage level is raised to that at the anode of the cathode-ray tube (+ 300 V).

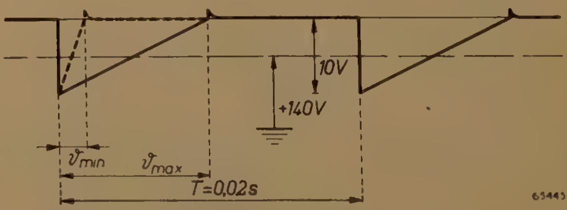

Fig. 24. Waveform of the voltage (taken from a multivibrator) which after amplification serves as time-base voltage of the oscilloscope. The duration of the stroke is variable between $\vartheta_{\max} = 0.01$ sec and $\vartheta_{\min} = 0.002$ sec.

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9) Cf. J. van Slooten, Philips Techn. Rev. **12**, 234, 1951 (No. 8), fig. 2.

The duration ϑ of the stroke is variable from 0.01 sec to 0.002 sec. A short stroke is chosen so as to spread a certain detail of the curve over the entire width of the screen. During the remaining part of the mains-voltage cycle the electron beam is suppressed by a square-wave voltage on the grid of the cathode-ray tube; this voltage is also supplied by the multivibrator.

When a short stroke is used the oscillogram is therefore traced only in a fraction of a cycle, and to give it sufficient luminosity for visual observation and photographic recording a cathode-ray tube with post-acceleration is used.

A small but practical detail is worth mentioning here. In article I it has already been shown how the step-response curve of the process analogue can be given a particular shape previously drawn on a sheet of cellophane, which is printed with a network of coordinates and placed in front of the oscilloscope screen. In the further use of the oscilloscope it is also desirable to have the network of coordinates visible together with the oscillogram. The background must then be much brighter than the darker lines of the coordinates, as is the case under ordinary circumstances but not when the light from the surroundings is cut off by a cylinder (K in fig. 12) with camera. Around the cathode-ray tube of the electro-analogue, behind the front plate, is a circle of small incandescent lamps uniformly illuminating the screen. Of course the brightness of the background must not be increased so far as to make the contrast with the luminescent trace too small. The current passing through the lamps is made variable so as to be able to adjust the brightness to the most favourable level.

Other parts

Fig. 25 shows a detail of the front of the electro-analogue. Here there are some parts which have not yet been discussed but which will now be dealt with briefly.

The square-wave generator has a fundamental frequency of 50 c/s. This square-wave voltage serves as input voltage for the process analogue when adjusting for a particular step-response, and also as a disturbance which can be introduced at various points in the control circuit. Part of the

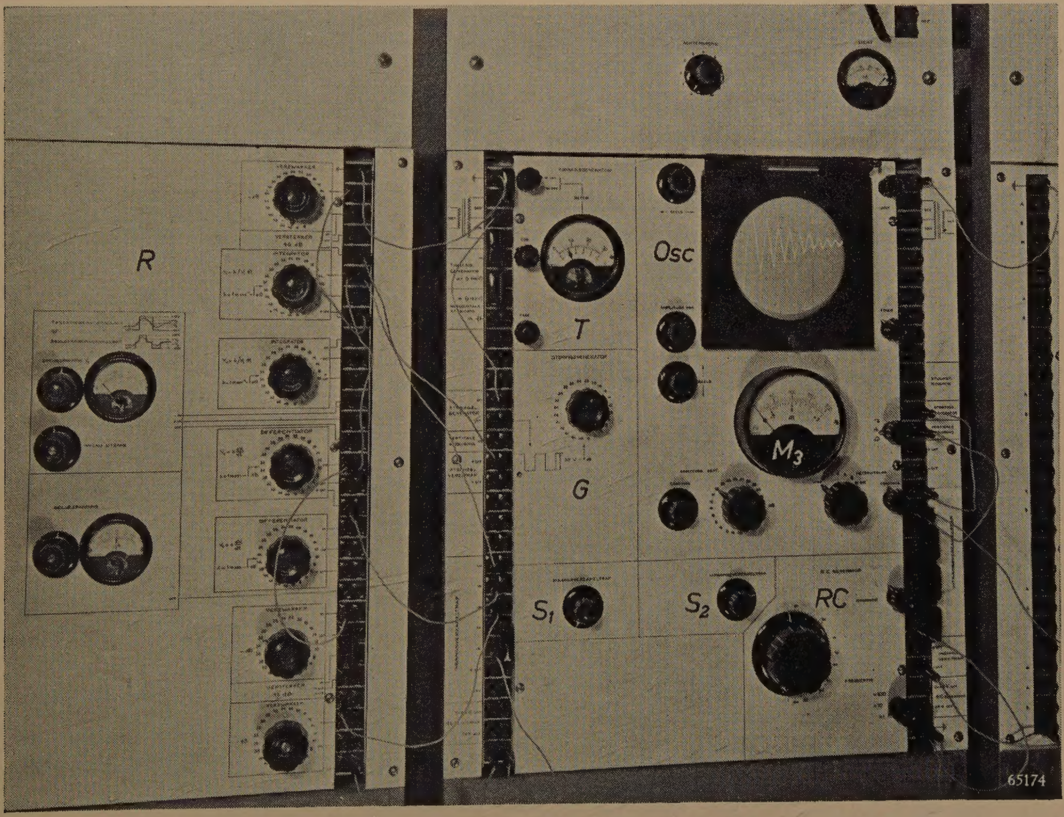

Fig. 25. Detail of the front of the electro-analogue. *Osc* oscilloscope with generator T of the time-base voltage, G square-wave generator, M_3 accuracy-measuring meter, S_1 input and S_2 output collecting stages, RC the R-C generator, R panel with controller models. Above the oscilloscope: control for adjusting the background brightness when photographing the oscillograms, and a micro-ammeter for measuring the intensity of the beam current.

circuit of the square-wave generator is shown in *fig. 26* and explained in the subscript.

For recording frequency-response curves and Nyquist diagrams, the electro-analogue is fitted with a sine wave generator. This is an *R-C* generator of a normal type with the frequency variable between 20 and 20,000 c/s.

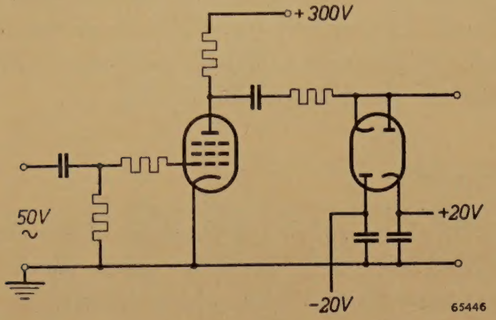

Fig. 26. A fairly large sinusoidal alternating voltage (50 V) alternately cuts off the pentode and makes it conducting, the anode voltage then varying between +300 V and about +10 V. This variation is limited by the double diode. In this way a square-wave voltage with an amplitude of about 15 V is obtained, which, attenuated or not, can be applied to the input of one of the collecting stages.

Finally mention is to be made of the performance meter with which one can determine how far the quantity to be controlled deviates from the value desired. As explained in article I, both the average of theabsolute values of x ($x =$ the instantaneous value of the deviation) and the r.m.s. value of x can serve as a measure for this deviation. Both these quantities can be read from a moving-coil meter, the first after full-wave rectification of x by means of a bridge circuit of selenium cells, the second by the intermediary of a thermocouple.

The supply

All the direct voltages needed in the electro-analogue are derived from stabilised rectifiers, of which there is a fairly large number (37!), each supplying only one or several parts. In this way a source of instability is avoided which would arise if all parts were fed from one common source, and which would be difficult to eliminate. Moreover this solution has the advantage that stabilised rectifiers for small powers can easily be made in such a way as to yield a highly constant voltage while having a low output impedance; this greatly reduces the danger of all sorts of difficulties arising.

It was possible to manage with only a few types by choosing suitable direct voltages and currents and, where necessary, connecting two or more rectifiers in series. An idea of what the back of the electro-analogue looks like can be formed from *fig. 27*, showing the numerous supply rectifiers.

By way of an example the supply diagram of the oscilloscope is given in *fig. 28*.

Although for the working of stabilised rectifiers we may refer to an article already published in this journal [10]), in *fig. 29* the main features of the system have been indicated

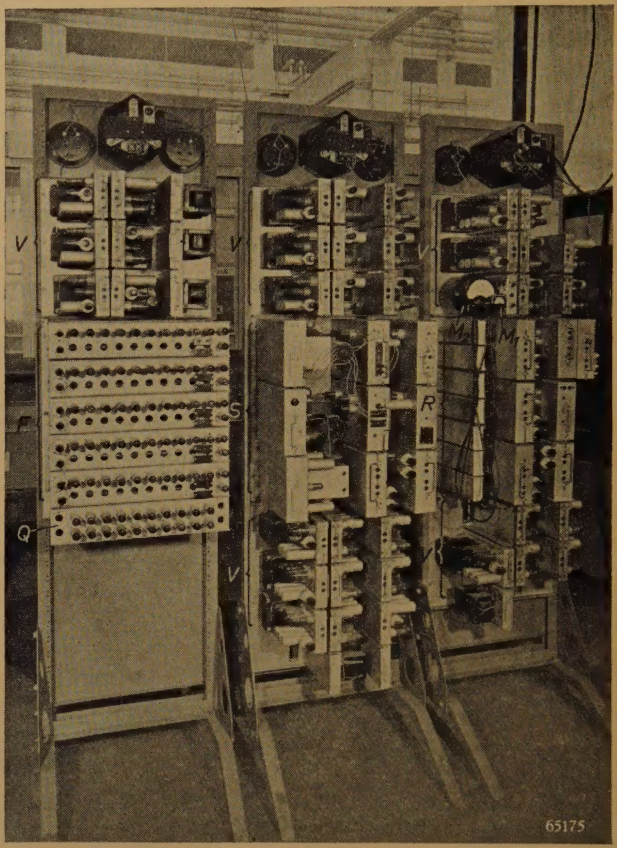

Fig. 27. Back of the electro-analogue. *V* stabilised supply rectifiers (37 in all), *F* delay network, *Q* special process analogues, *S* oscilloscope and various other parts, *R* parts of controller models, M_1 meter for checking the uniformity of the D.C. voltage levels (cf. subscript to fig. 13), M_2 D.C. voltmeter, which can be connected to the various rectifiers.

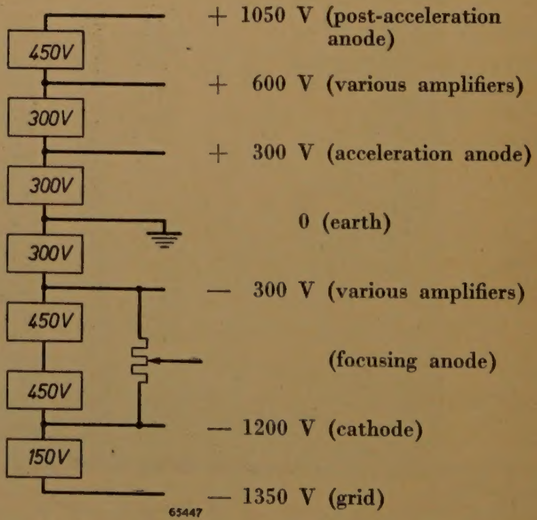
450V
300V
300V
300V
450V
450V
150V
+ 1050 V (post-acceleration anode)
+ 600 V (various amplifiers)
+ 300 V (acceleration anode)
0 (earth)
— 300 V (various amplifiers)
(focusing anode)
— 1200 V (cathode)
— 1350 V (grid)
65447

Fig. 28. Lay-out of the supply circuit for the oscilloscope.

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[10]) H. J. Lindenhovius and H. Rinia, A direct current supply apparatus with stabilised voltage, Philips Techn. Rev. 6, 54-61, 1941.

so as to be able to explain the essential elements of a regulating circuit 11). The valves UL 41 connected in parallel form, as it were, a regulating unit the "position" of which is governed by the valve UF 41, which acts as controller and is influenced by the voltage that is to be kept constant. Here we have a proportionately acting controller. The offset is therefore not zero, but thanks to the high gain of the controller it is in any case very small.

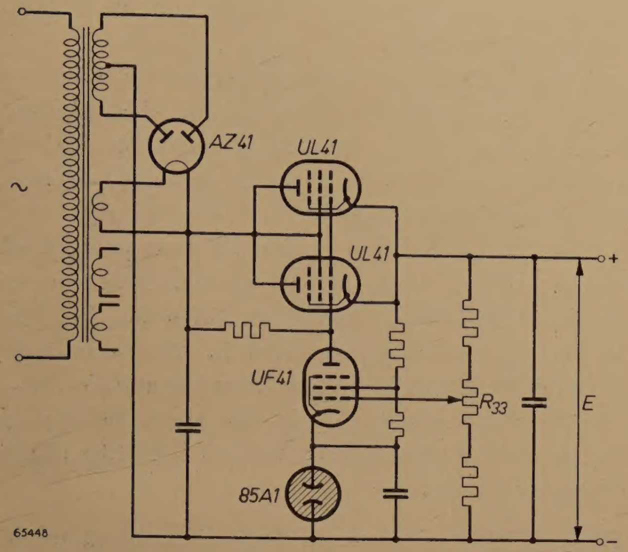

Fig. 29. Circuit diagram of a stabilised rectifier for 50 mA. AZ 41 rectifying valve, UL 41 parallel-connected pentodes used here as triodes ("regulating unit"), UF 41 amplifying valve ("controller"). The input voltage for the controller consists of the difference between a part (variable with the potentiometer R_{33}) of the direct voltage E and the stabilized voltage kept constant by the voltage reference tube 85 A1.
In addition to this type for 50 mA (and different voltages), also a type for 100 mA is used in the electro-analogue. This works with two parallel-connected AZ 41 valves and three parallel-connected UL 41 valves.

Mechanical construction

The components of the electro-analogue are mounted on interchangeable chassis, with the electrical contacts made by means of plug pins and sockets (*fig. 30*). For each type of part there is a spare duplicate which in a few moments can be put in to replace a defective part, so that in the case of a breakdown there is no need to wait until the cause has been traced and remedied. The construction of the chassis is such that all the elements mounted on them and all the wiring are easily accessible. With the chassis placed in the vertical position (see fig. 27) there is the least possible obstruction to the circulation of air.

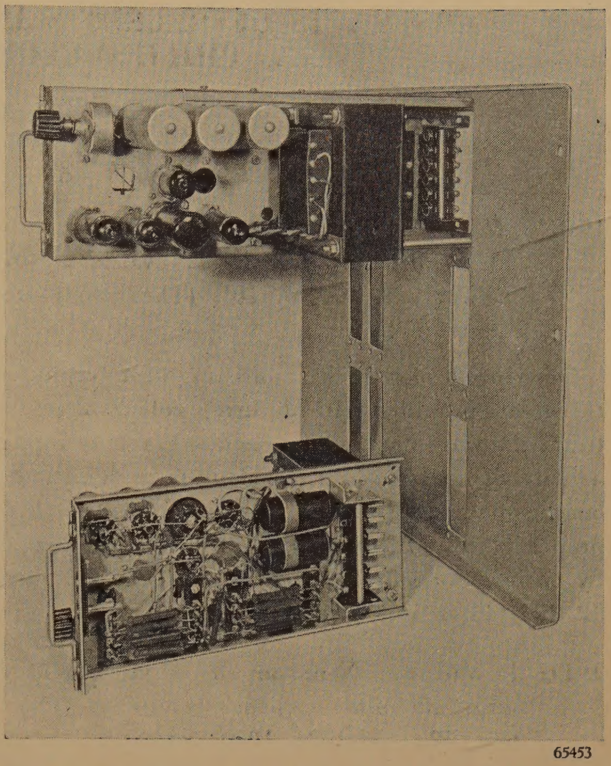

Fig. 30. Illustration of the interchangeability of the parts mounted on separate chassis. The mounting plate on the right can carry 9 chassis, one of which (at the top) with its guiding frame is shown here drawn out half way — this is the chassis of a supply rectifier for 50 mA. Below is an identical rectifier unit seen from the other side; note the easy accessibility of all elements, and the plug pins for making contact with sockets on the guiding frame. On the extreme left of the two chassis are sockets to which a voltmeter can be connected, and also the knob for adjusting the direct voltage to a certain value.

Supporting the chassis are mounting plates screwed onto the back of the panels on which the electro-analogue is mounted. In front of these plates are the permanent leads forming the connections between the chassis and, among others, some rows of plug sockets. By means of these plug sockets and separate leads the circuits required can be connected up. Finally the wiring compartments are shut off with front plates (fig. 25).

The construction described here has proved to be quite satisfactory for the assembling of a complicated system like that of the electro-analogue.

Summary. As a continuation to an article in which the parts used in making up the electro-analogue and the results that can be achieved with it have been described, the electric circuits of these parts are dealt with more closely. In the "planning" of the electro-analogue the fundamental idea was that it should be possible to get any desired combination of parts by plugging in separate connecting leads. All input and output terminals must therefore have the same direct-voltage level. The method usually followed for such a purpose — employing separating capacitors and leak resistors — cannot be considered in this case, because the large number of these *R-C* couplings which would have to be contained in the control circuit would lead to instability. Instead of these couplings, voltage dividers have been used, which provide for the correct direct-voltage level; not only positive but also negative supply voltages are needed for this, and moreover these have to be carefully stabilised.

Among the various parts discussed in this article are: the process analogues, the universal amplifier, the collecting stages, the integrator and the differentiator, models of discontinuously acting controllers, the oscilloscope, the supply and the mechanical construction.

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11) Cf. H. J. Roosdorp, On the regulation of industrial processes, Philips Techn. Rev. 12, 221-227, 1951 (No. 8).

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of these papers not marked with an asterisk can be obtained free of charge upon application to the address printed on the back cover.

1948*: W. de Groot and A. A. Kruithof: De kleurendriehoek (Ned. T. Natuurk. **16**, 235-241, 1950, No. 10). (The colour triangle; in Dutch.)

Description of a device consisting of a system of three slits provided with diffusing colour filters, a triangular screen and a triangle diaphragm covering a plate of opal glass. The colour triangle appears on the opal glass with the different colours in their proper places, when the three slits are illuminated by an incandescent lamp (See Philips Techn. Rev. **12**, 137-144, 1950, No. 5).

1949: J. Volger: Note on the Hall potential across an inhomogeneous conductor (Phys. Rev. **79**, 1013-1024, 1950, No. 6).

The change in the potential function in a homogeneous conductor of rectangular shape due to the Hall effect has been calculated to the first approximation. Some important conclusions are drawn for the case of an inhomogeneous conductor.

1950: R. van der Veen: Induction phenomena in photosynthesis, III (Physiologia Plantarum **3**, 247-257, 1950, No. 3).

It has been shown that the reaction of Chlorella to sudden illumination is much different from that of higher plants. While higher plants always begin with an initial uptake of CO_2, Chlorella does exactly the opposite and begins with a release of CO_2 before it starts photosynthesizing. This sudden release of CO_2 is positively correlated with light intensity, negatively with temperature and positively with the duration of the preceding dark period.

Another difference between higher plants and Chlorella is the "de-adaptation" in darkness. In Chlorella there is not much difference in adaptation time after short and after long dark periods. In higher plants, however, after long periods of darkness adaptation takes much longer than after short periods of darkness.

A third difference is the behaviour of Chlorella in pure hydrogen without any CO_2. In this environment higher plants react to illumination with a sudden releas of oxygen, which could not be found when examining Chlorella.

Thus Chlorella has a rather different pattern of photosynthesis than higher plants. Protococcus olivaceus Rabenh., which, like Chlorella, belongs to the Protococcales, behaves in the same way as Chlorella. Ulothrix sp, like Hormidium flaccidium and Stichococcus bacillaris, all three belonging to the Ulotrichales, have induction lines like those of higher plants.

1951: H. O. Huisman: Investigations on quinones and quinone derivatives. Preparation and antibiotic properties of some substituted p-benzo- and p-toluo-quinones, hydroquinones and hydroquinone esters (Rec. Trav. chim. Pays-Bas **69**, 1133-1156, 1950, Nos 9 and 10).

The antibiotic properties of the compounds named in the title have been tested in vitro against a yeast, various moulds and Gram-positive and Gram-negative micro-organisms. The toxicity has been determined in white mice by oral administration and by interperitoneal injection. The chemotherapeutic activity has been investigated in white mice injected with a lethal dose of pneumococci.

1952*: P. Cornelius: Electrische eenheden en het Giorgistelsel (Electrotechniek **28**, 454-460 473-479, 1950 Nos 23 and 24). (Electrical units and the Giorgi system; in Dutch.)

Review of the Giorgi system of units; see Nos **R 103**, **R 111**, **R 151** and Philips Techn. Rev. **10**, 55-60, 79-86, 1948.